

6<sup>th</sup> International Planetary Probe Workshop, Atlanta, Georgia  
Short Course on Extreme Environments Technologies

06/21-22  
2008

*set the controls  
for the  
**Heart of the Sun:***  
power & mobility  
for high temperature environments



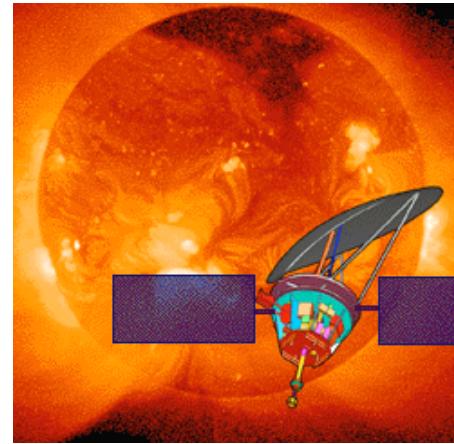
**Geoffrey A. Landis**  
NASA John Glenn Research Center  
Cleveland, OH

# High-temperature Mission Environments

Many High Temperature mission applications

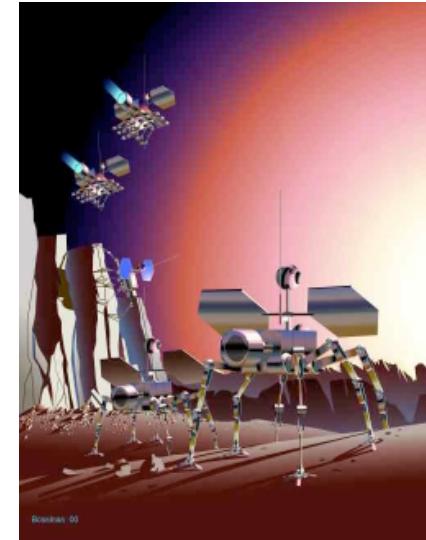
## Space Applications:

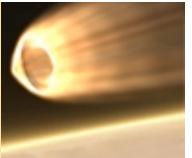
- Venus
- Mercury
  - both surface & orbit
- Solar Probe
- Io Volcanoes
- Jupiter deep atmosphere



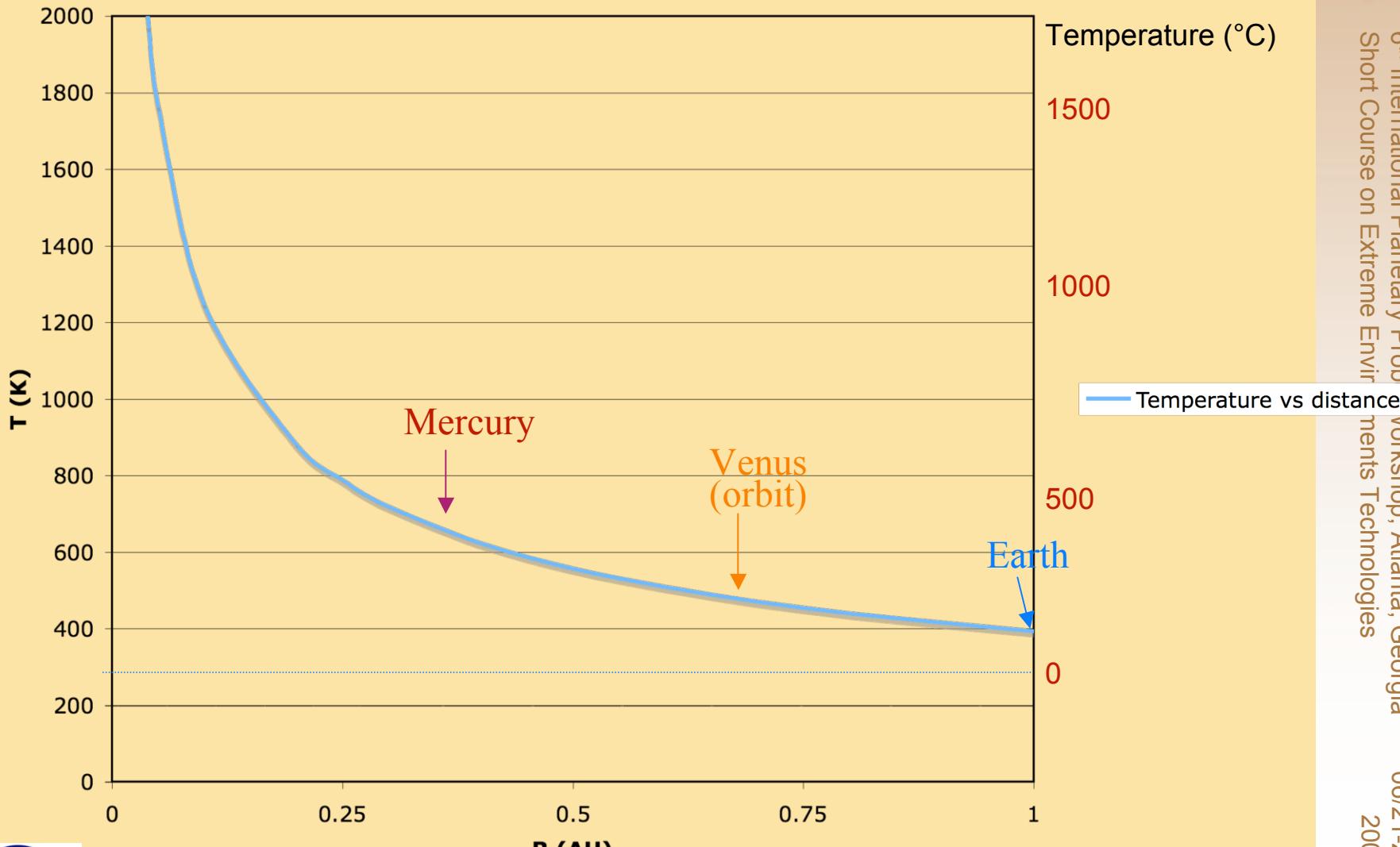
## Terrestrial applications

- Volcanos (e.g., "Firewalker" mission)
- thermal vents
- Down-hole drill applications





Things get hot as you move toward the sun!



Equilibrium Temperature vs distance from sun

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- Temperature of a surface flat on to the solar flux

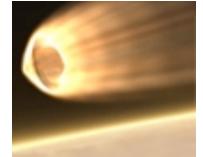
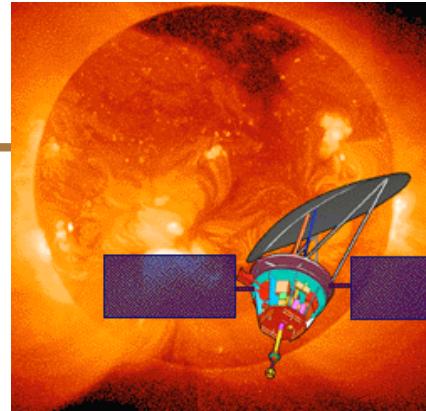
# Environments: temperatures

Many High Temperature mission applications

## Space Applications:

- Venus (surface) 390 to 480°C
- Mercury (surface) -150 to 425°C
- Solar Probe 1200 to 2000° C
- Io Volcanoes 1250 to 1300° C
- Jupiter deep atmosphere

**temp increase=2.2°C/km**  
(Galileo probe failed at 23 bars, 152°C)



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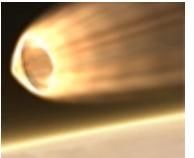
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## Terrestrial applications

- Volcanos 800-1200°C
- thermal vents up to 403°C
- Down-hole drill applications

**100°C and up**  
(varies with depth)





## Power: needed for all space missions

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Visualization by John Frassanito Associates



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# Power Choices

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Photovoltaic arrays ("Solar Cells"): **performance degrades as temperature increases**

Degradation is reversible up to some materials-limitation (typically 300-400C)

Thermal conversion (Nuclear power sources, RTG, solar-thermal conversion): **Thermodynamic conversion requires "cold end" for heat rejection; power degrades as cold-end temperature increases**

Batteries: OK for short missions, but will require power source to recharge for long mission





## Solar Cells: overview

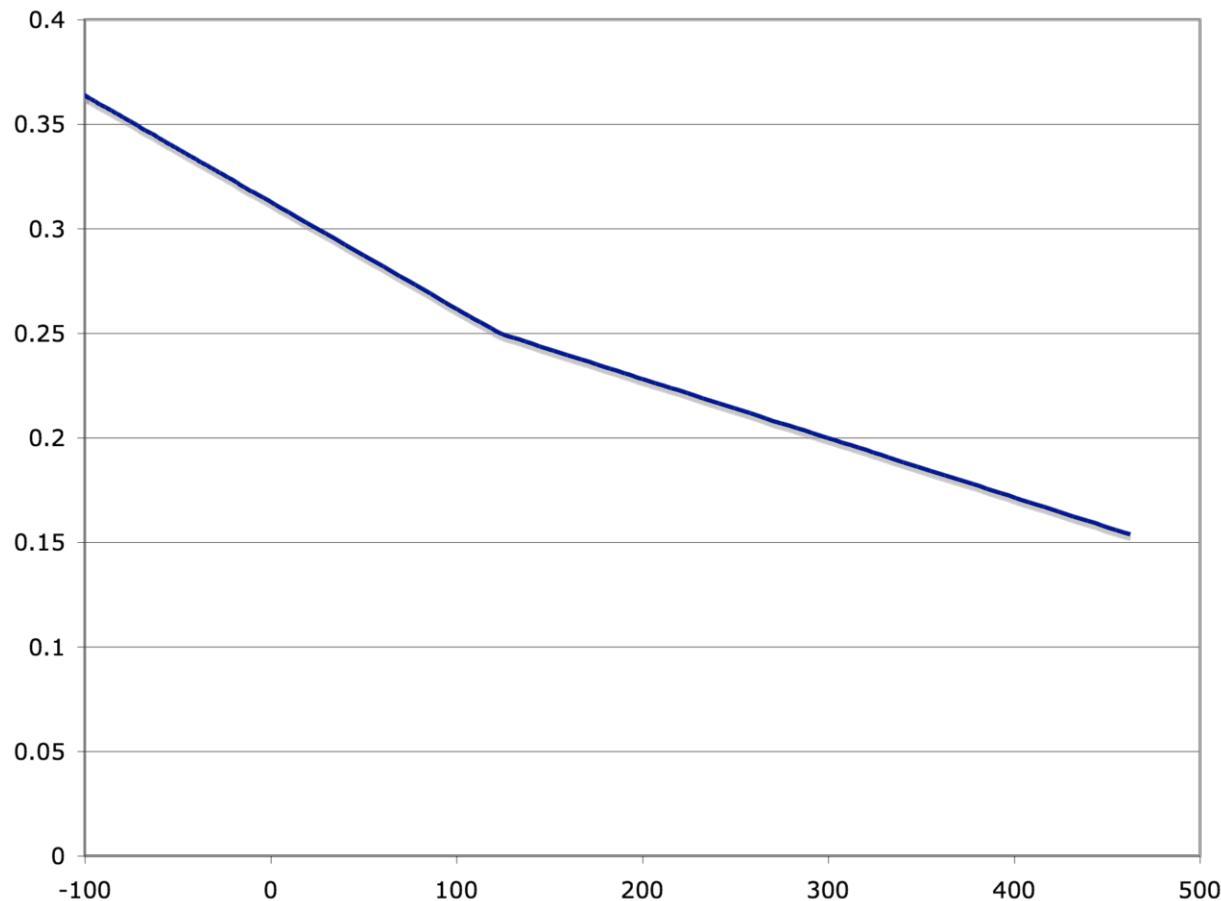
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- High-temperature operation of solar cells is of interest to future NASA missions
- Technology solutions such as off-pointing can reduce operating temperature, but also reduce power from the array
- New solar cells that can operate at high temperature are desirable; this requires development of high bandgap semiconductors
- Achieving satisfactory operating lifetime at high temperature is an issue that has not yet been addressed





# Solar Cell: effect of temperature on Efficiency



Data is for typical 3-junction space  
GaInP2/GaAs/Ge space cell



# Thermal Control for Solar Arrays



This is a problem because solar arrays must be exposed to the sun....

## Some approaches to thermal control:

- High epsilon/low alpha coatings

Stefan-Boltzmann law: heat radiated is proportional to epsilon

- Array off-pointing: array points at angle to sun

incident power decreases as cosine of solar normal angle

- Partially-populated array (cells replaced with reflectors)

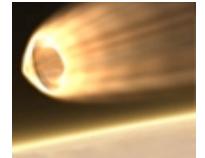
reflectors designed for low absorptance, high emissivity

- Reflective coatings

preferentially reflect light that is not used by cell

- Solar cells redesigned to optimize power at high T





## Operating Temperature and Performance

from Stefan-Boltzmann law:

$$\alpha I = (\varepsilon_f + \varepsilon_r) \sigma T^4$$

(here we define the absorptivity  $\alpha$  as the net energy absorption, incorporating a factor of  $(1-\eta)$ )

$$T = [(\alpha / (\varepsilon_f + \varepsilon_r) \sigma) I]^{1/4}$$

The (unnormalized) coefficient of efficiency  $k^*$  is defined as:

$$k^* = d\eta / dT$$

and the power at a temperature  $T$  is:

$$P = (\eta_{300K} + k^* \Delta T) I$$

Thus

$$P = I (\eta_o + k c I^{1/4}) = I \eta_o + k c I^{5/4}$$

where:

$$c = [\alpha / (\varepsilon_f + \varepsilon_r) \sigma]^{1/4}$$

**\*Note  $k < 0$**



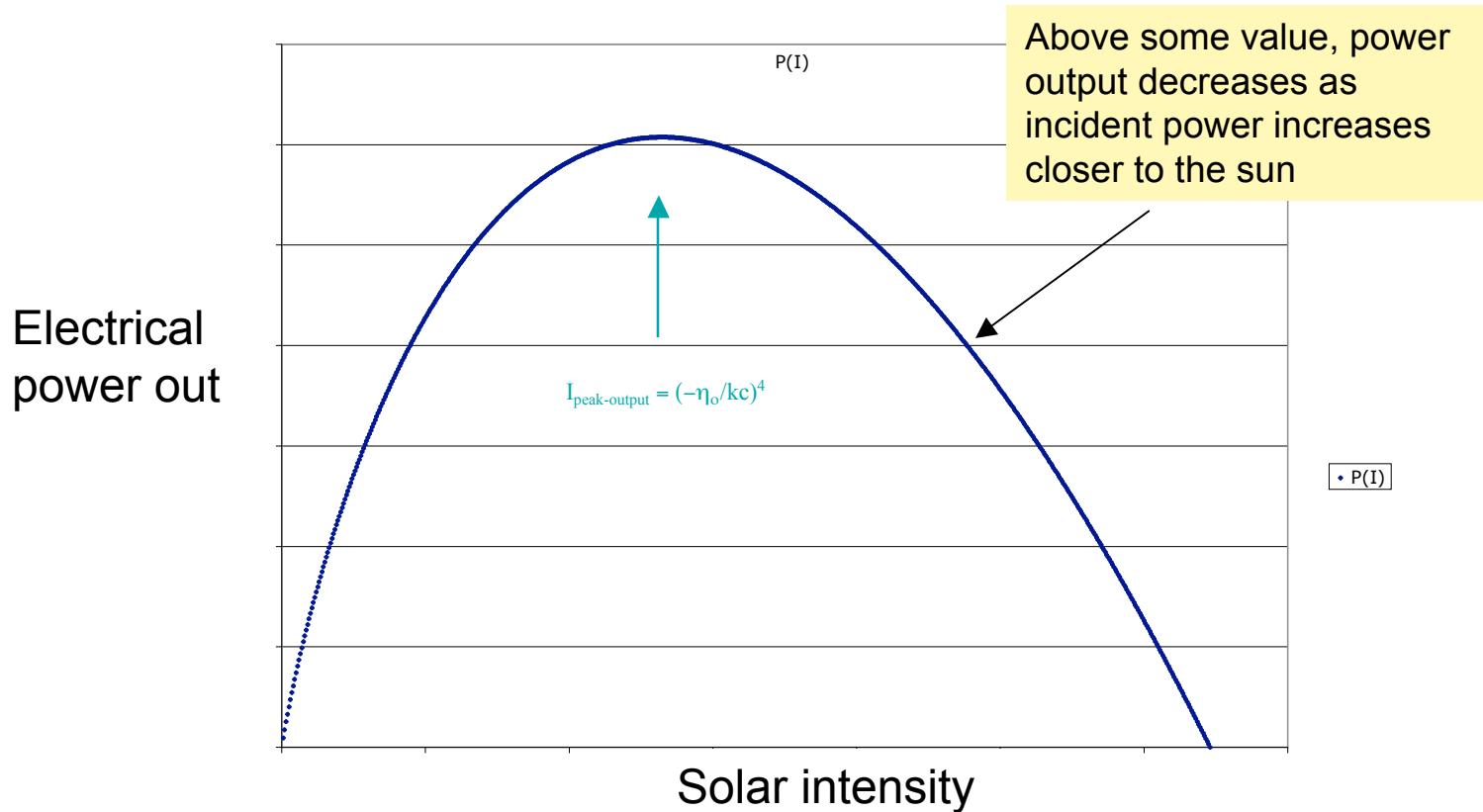
# Solar-Array Power output as a function of incident intensity

(for case where solar array is at equilibrium temperature with solar input)



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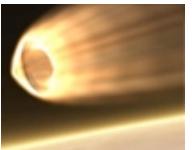
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$$P = I \eta_o (1 + kc/\eta_o I^{1/4})$$

\*Note  $k < 0$

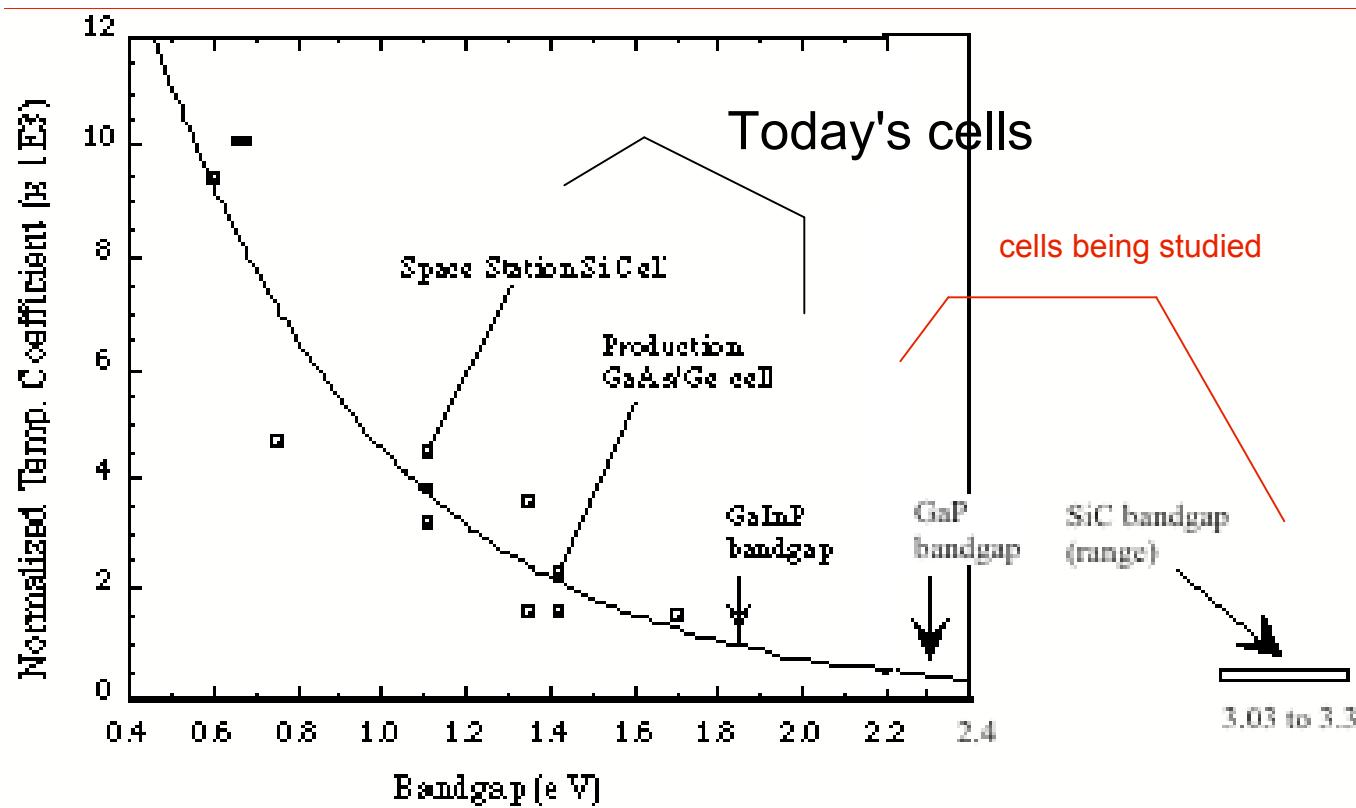




## Temperature Coefficient depends on the solar cell material

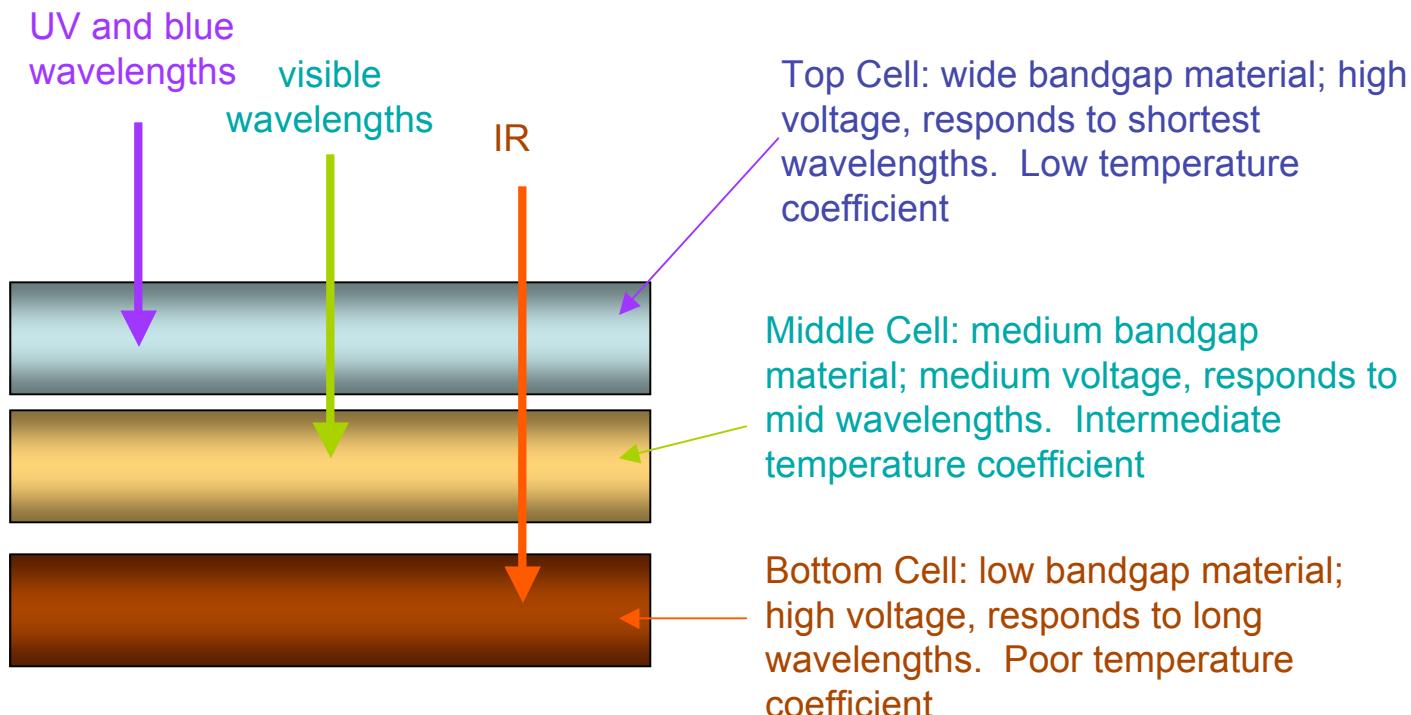
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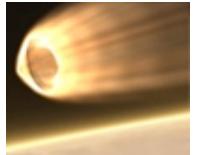
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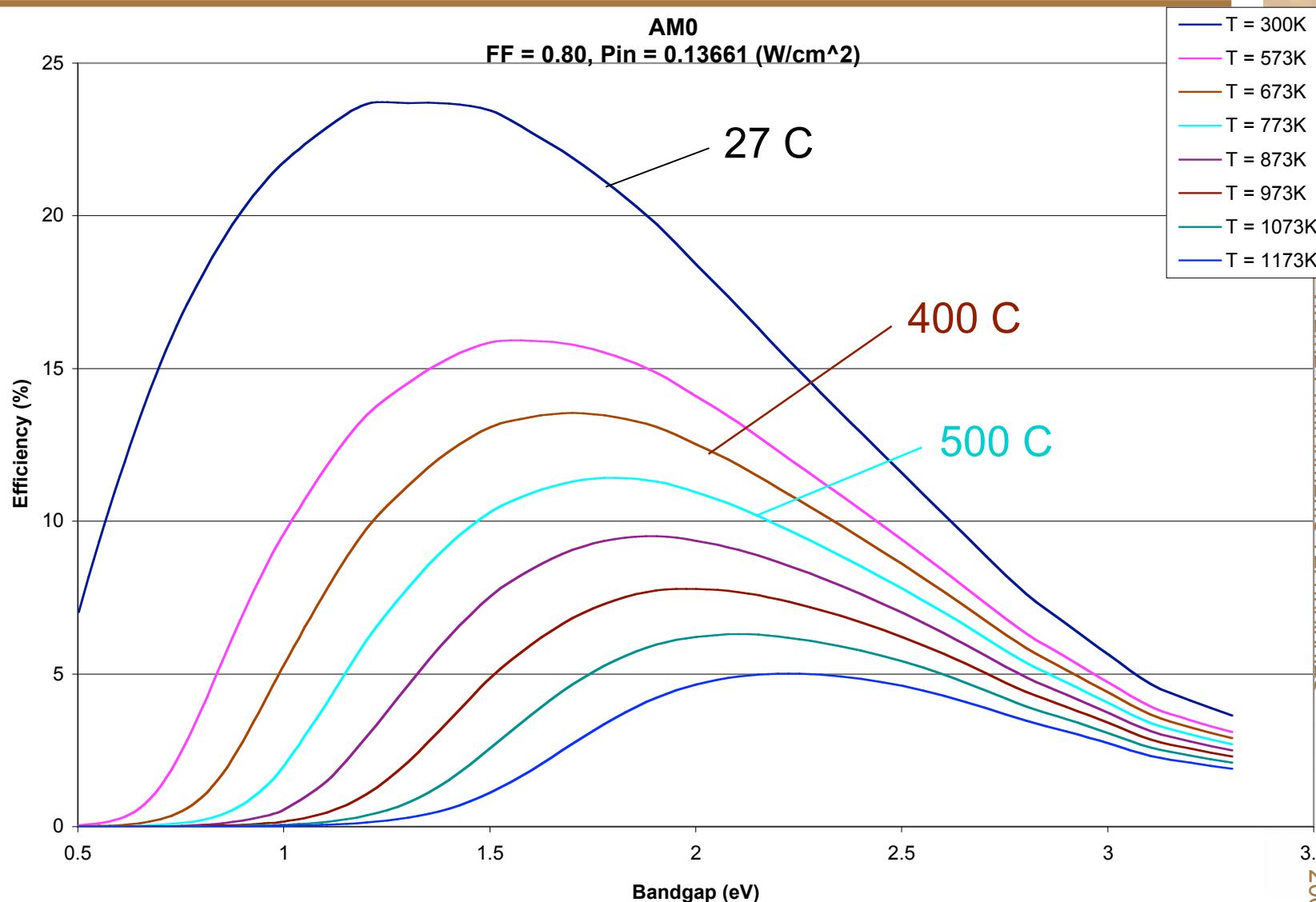


# Solar Cell Design: triple junction cell





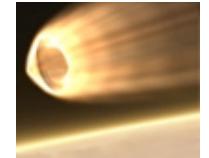
## Theoretical calculations of efficiency vs bandgap



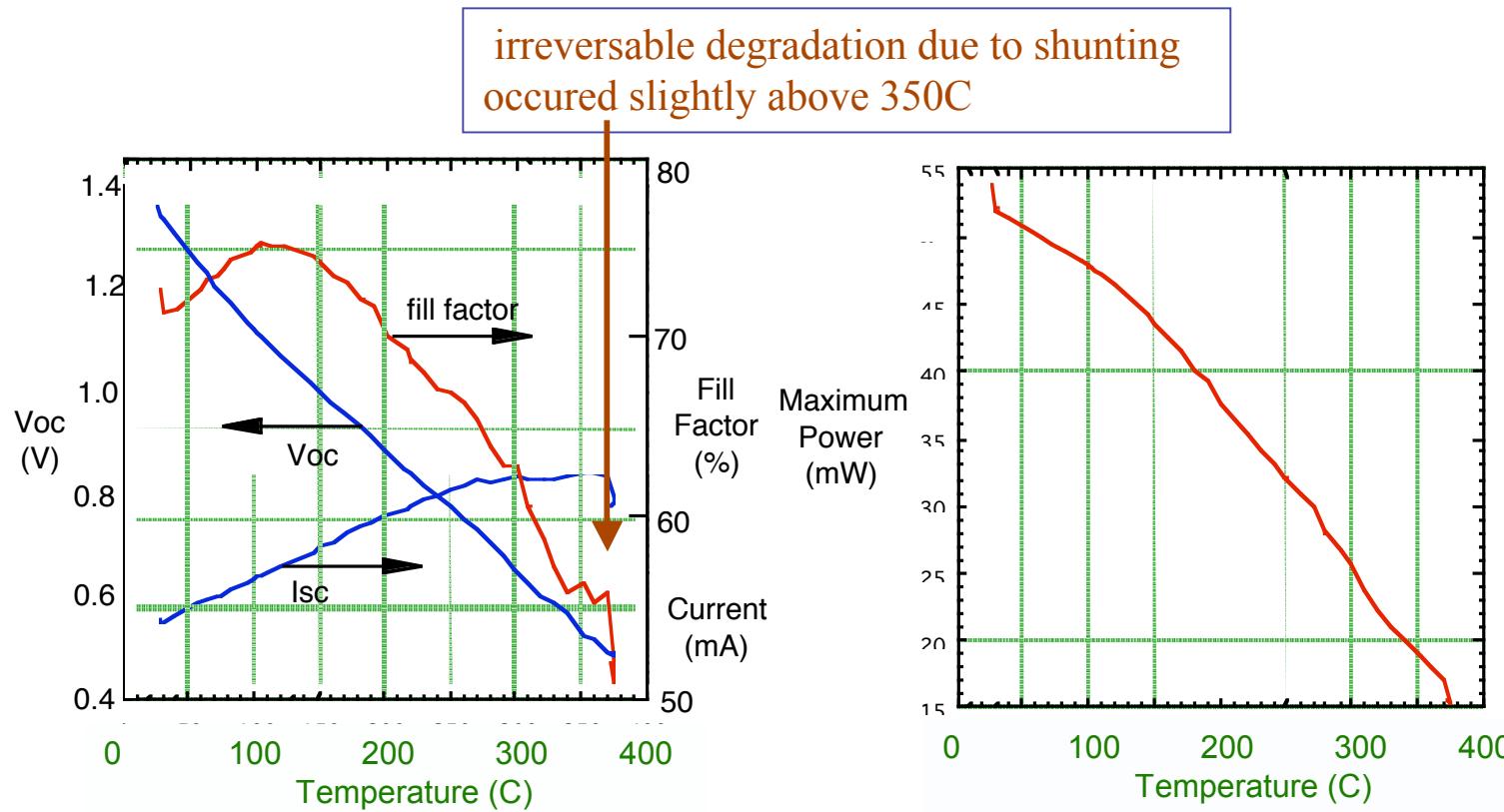
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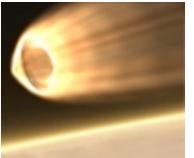


## Example Test results: GaInP cell



GaInP solar cell parameters measured as a function of temperature, from 0 to 400 C. Open circuit voltage and fill factor decrease with temperature, while the short circuit current shows a slight increase. Power loss [1/P dP/dT] is about 0.177% per degree.





# Lifetime issues

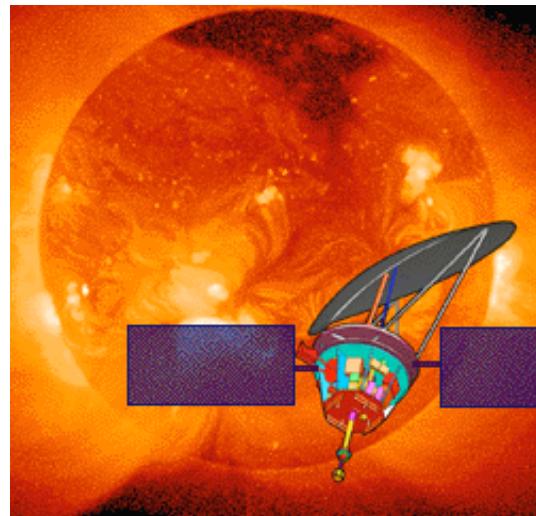
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At some critical temperature, irreversible degradation of the cell sets in

- Ohmic contact degradation
- Dopant diffusion
- Compound semiconductor degradation
- Critical temperature for irreversible degradation depends on materials and processing. Highly stable metallization and barrier layers can extend the operating range considerably.

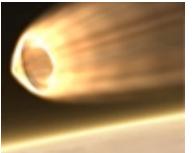
## Other thermal issues

- Interconnects
- Coverglass adhesive
- Array structure
- Thermal cycling stress



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## Thermal Conversion

An alternate power source is thermal conversion.

Thermal source: nuclear isotopes, nuclear reactors, solar heating

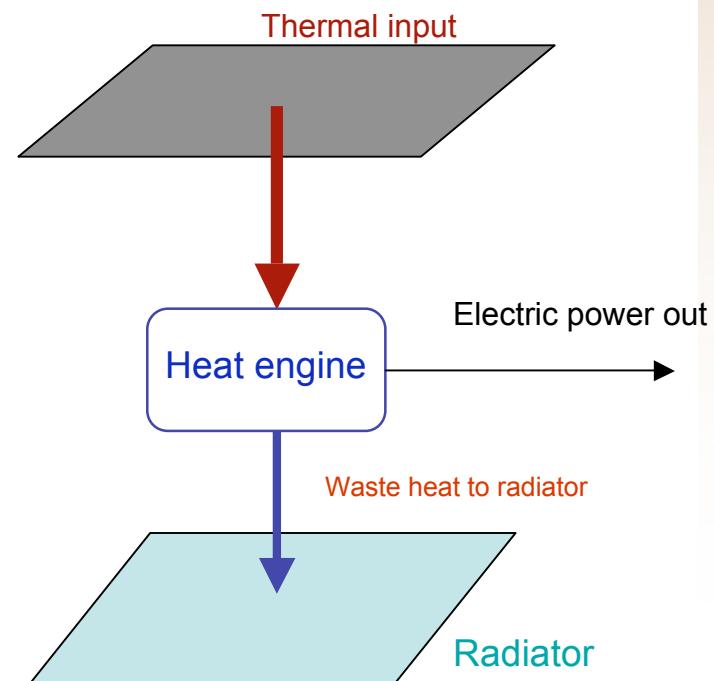
Many different types of thermal conversion: dynamic ("heat engines"; Stirling conversion, Brayton), and static (thermoelectric)

A heat engine runs off a **temperature differential** between hot and cold sides

Efficiency is proportional to  $(T_{\text{hot}} - T_{\text{cold}})/T_{\text{hot}}$   
 $= 1 - (T_{\text{cold}}/T_{\text{hot}})$

For high temperature operation, the limiting factor becomes the rate at which you can reject heat to the cold side

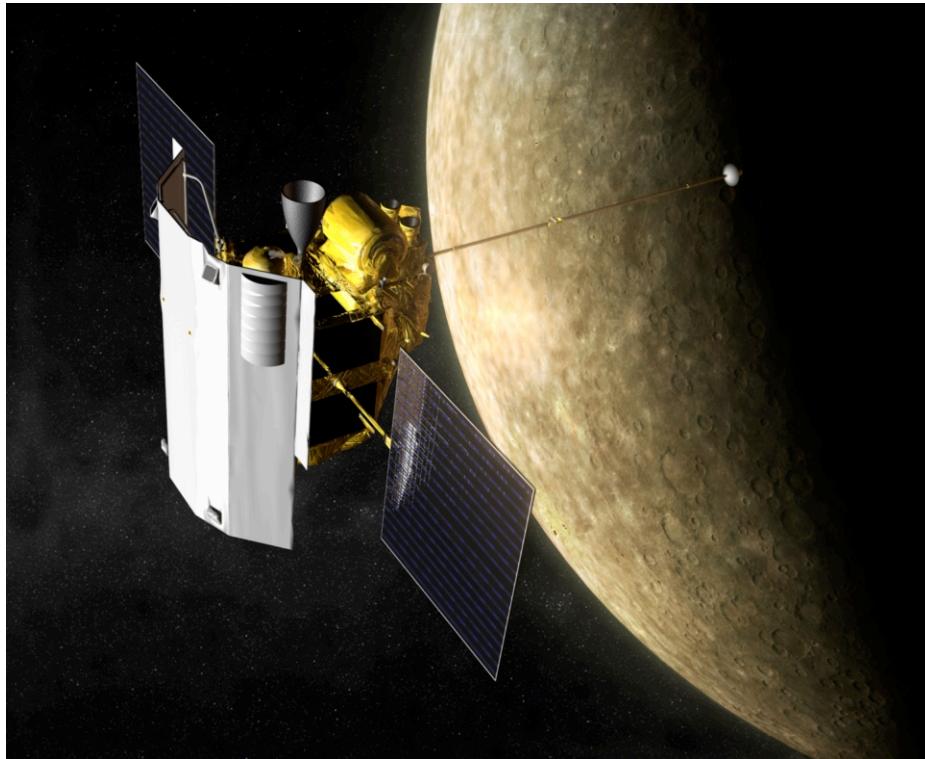
**Needs a radiator**





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MESSENGER mission



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# MESSENGER:

## How to keep solar arrays cool when you're close to the sun...



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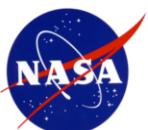
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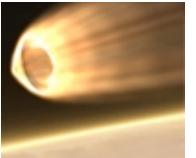
- Point the arrays off of solar normal
  - Decrease effective solar flux by a factor of cosine theta
- Replace solar cells by optical reflectors
  - 2/3 of the array area is mirrored does not absorb solar energy
  - Full surface of array can radiate in IR
  - Temperature reduced by factor  $(1/3)^{1/4}$



MESSENGER Solar arrays

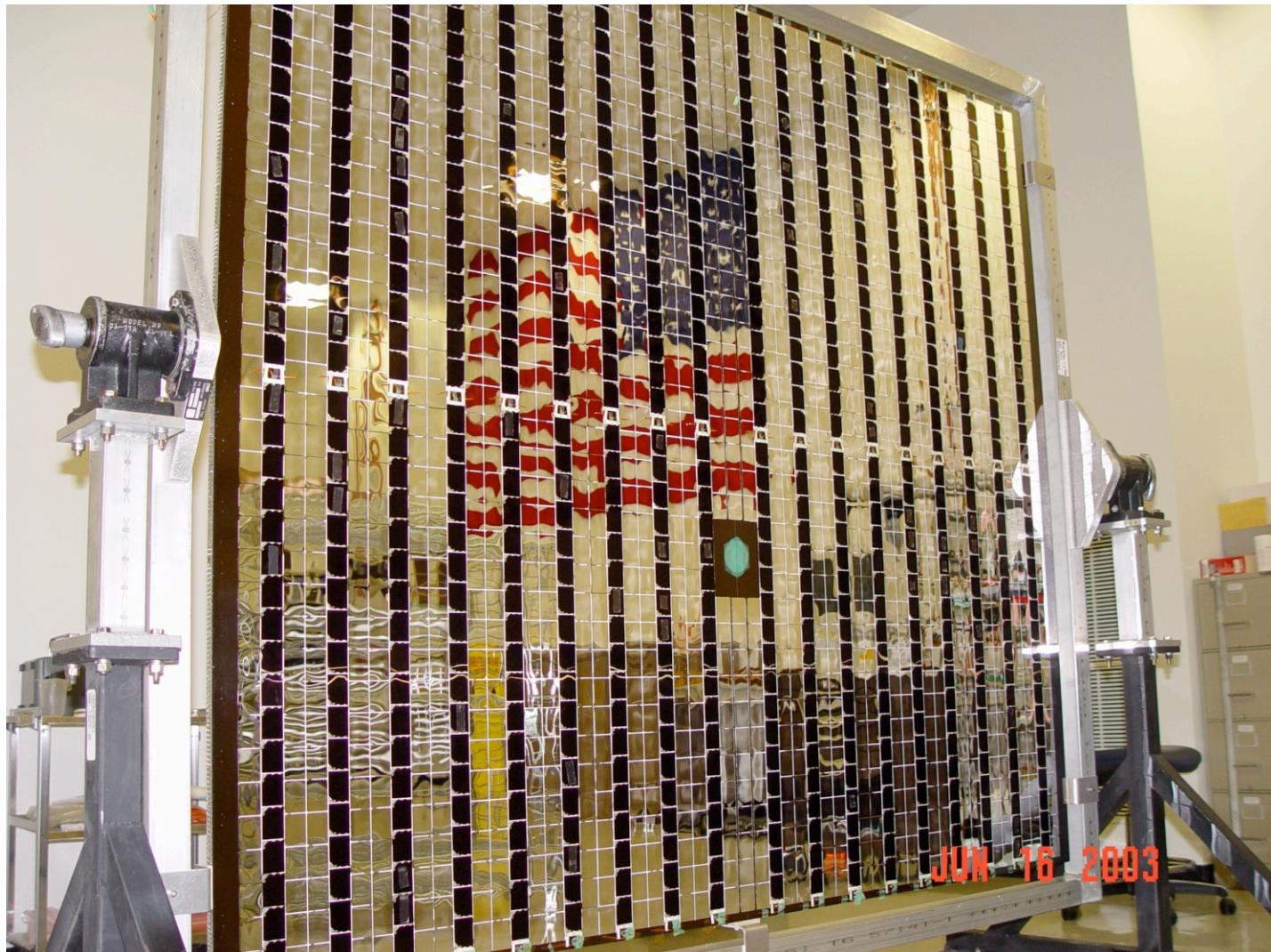
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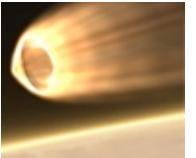


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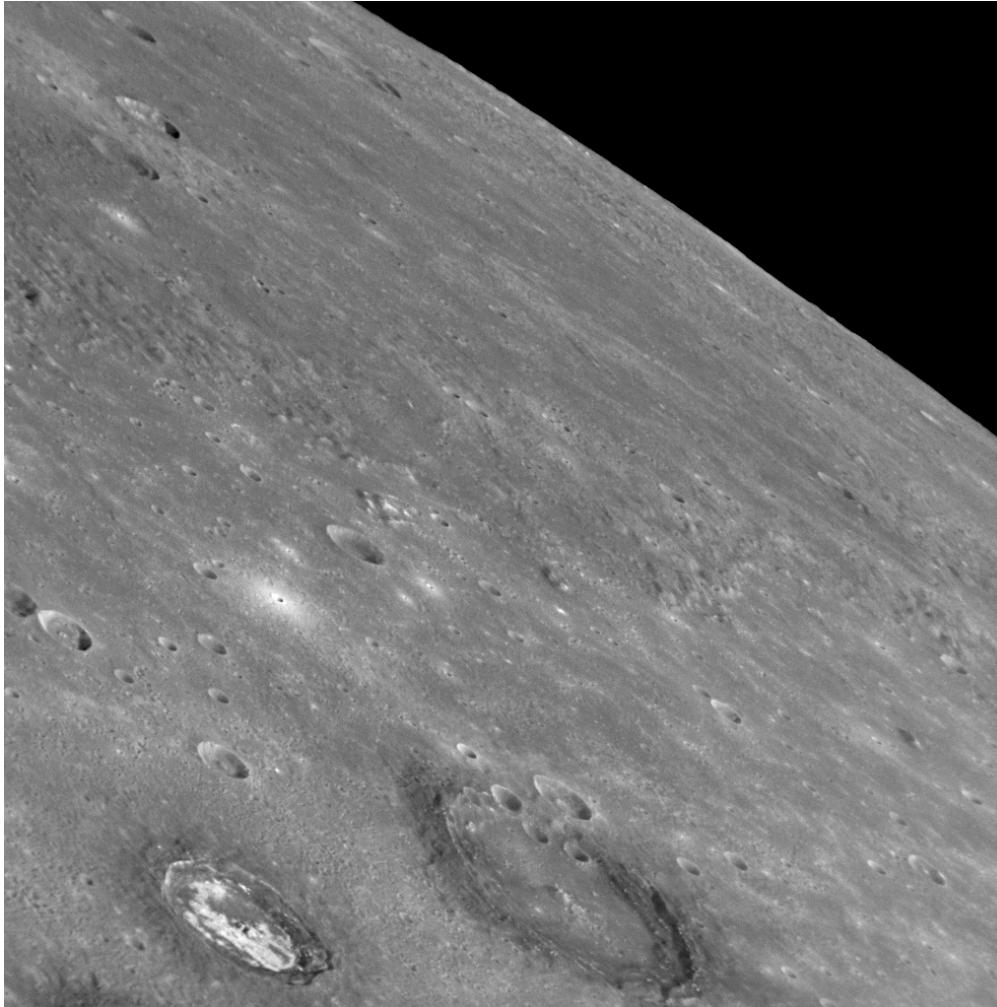
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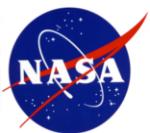
## MESSENGER success

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**Photo of Mercury from first flyby**  
bottom of Caloris basin

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# Design Study: Solar Probe...

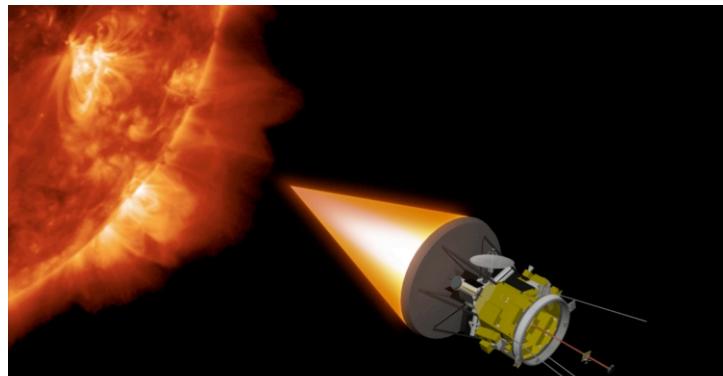
*Set the controls for the edge of the sun*

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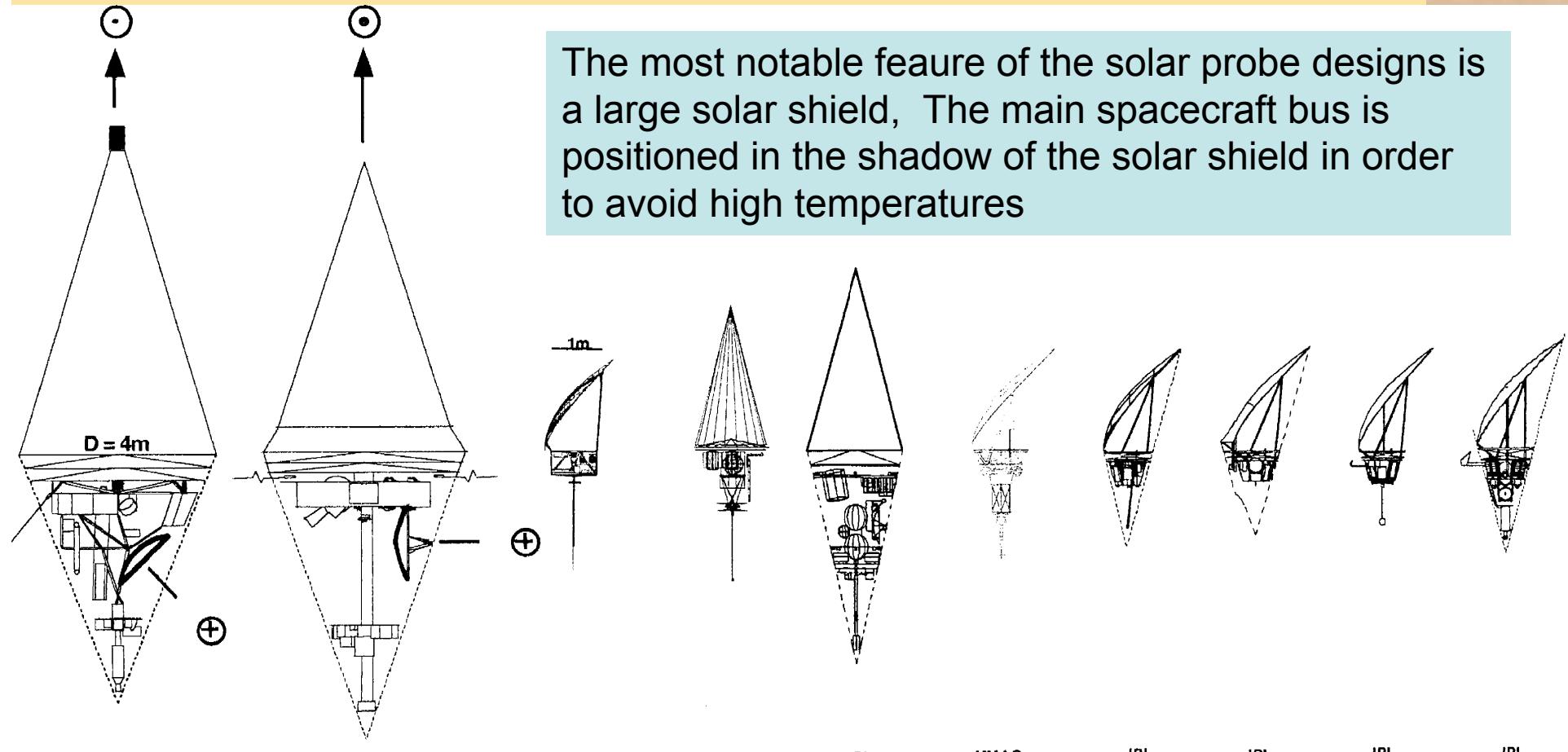
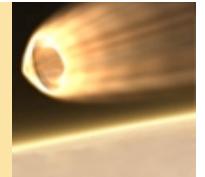
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Conceptual diagram of Solar Probe



# Solar probe designs, 1982-1999



JPL  
1982  
PLSMA= 117 kg  
+ IMAGING  
1100kg/700W  
STS/Centaur  
 $\Delta V$  - EJGA  
 $> \$1300M$

JPL  
1989  
PLSMA P/L= 133 kg  
1250kg/400W  
Titan/Centaur  
 $\Delta V$  - EJGA  
 $\$1000M$

MMAG  
1992  
PLSMA = 26 kg  
160kg/70W  
Delta/Star 30  
JGA  
 $<\$250M$

JPL  
1993  
PLSMA = 17 kg  
290kg/120W  
Atlas/Star 48  
JGA  
 $<\$400M$

APL  
1994  
PLSMA = 60 kg  
925kg/255W  
Atlas/Star 48  
 $\Delta V$  - EJGA  
 $<\$250M$

MMAG  
1994  
PLSMA = 12 kg  
180kg/80W  
Delta/Star 30  
JGA  
 $<\$250M$

JPL  
1994  
PLSMA = 17 kg  
200kg/100W  
Delta/Star 30  
JGA  
 $<\$220M$

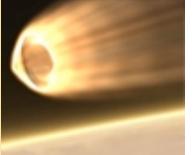
JPL  
1995  
PLSMA = 11 kg  
+ IMAGING  
194kg/80W  
Delta/Star 30  
JGA  
 $<\$170M$

JPL  
1997  
PLSMA = 15 kg  
+ IMAGING  
200kg/100W  
Delta/Star 30  
JGA  
 $<\$150M$

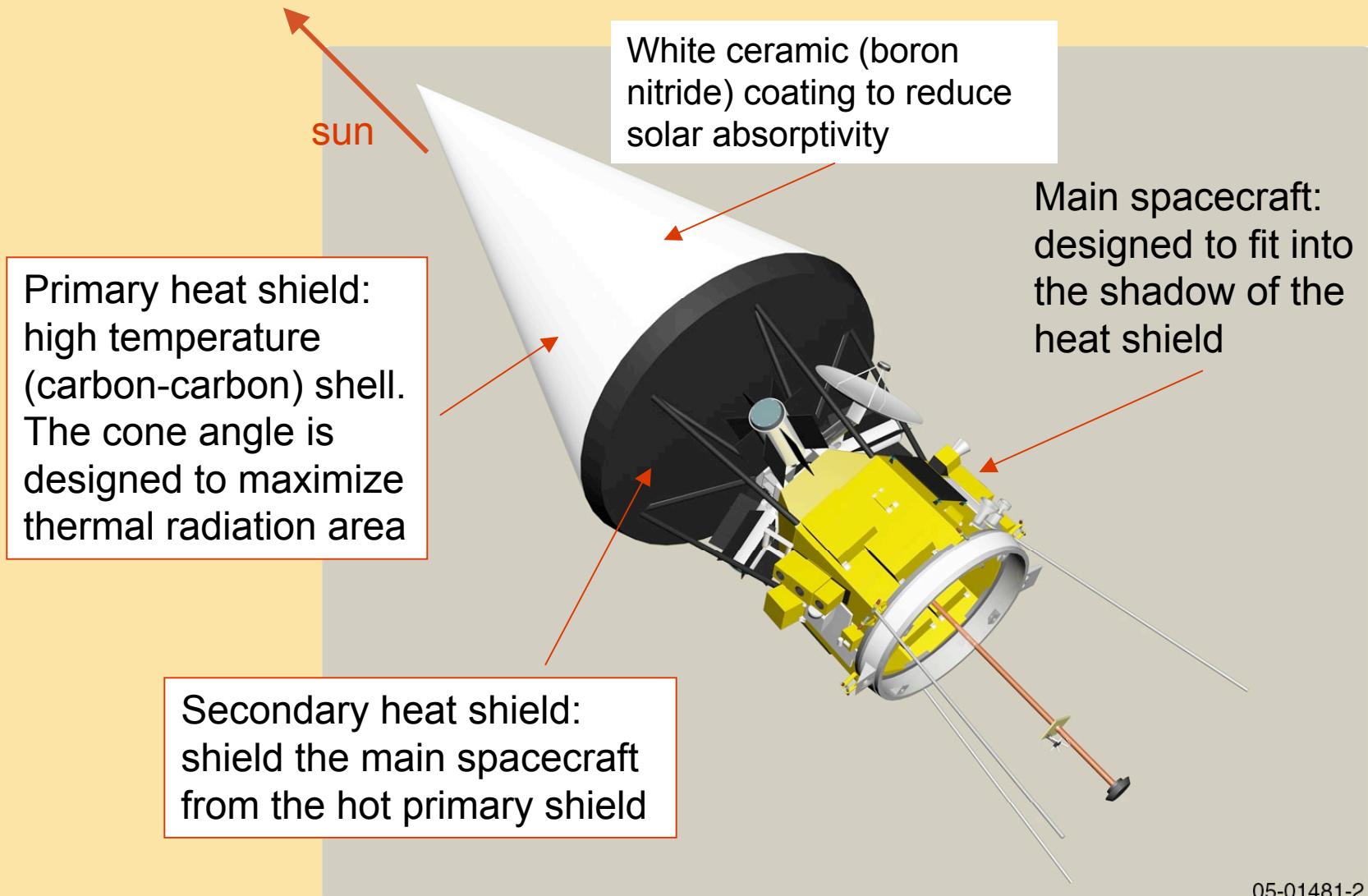
JPL  
1999  
PLSMA = 20 kg  
+ IMAGING  
250kg/250W  
Delta III/Star 48  
JGA  
 $<\$200M$

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## Solar probe conceptual design 2006



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[http://solarprobe.gsfc.nasa.gov/spes\\_fig5.jpg](http://solarprobe.gsfc.nasa.gov/spes_fig5.jpg)

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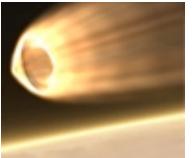
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## Difficult problem: solar power for near-sun operation

- Close to the sun the main part of the spacecraft hides behind the heat shield
- Power Source needed to operate at intensity from 16 to **520** times AM0 ( $\sim 700 \text{ kW/m}^2$ )

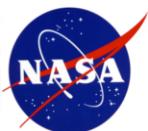


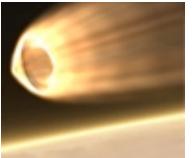


## PV or Thermal conversion?

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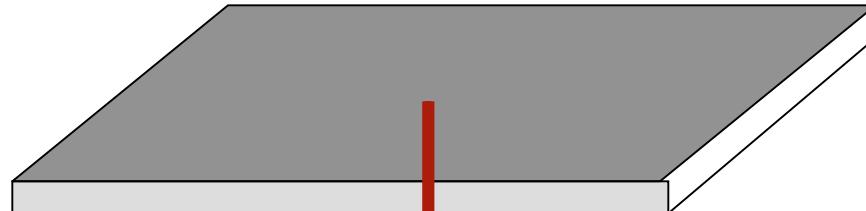
- Close to the sun the heat shield gets very hot
- Can thermal energy conversion be used to convert this heat to usable power?
  - Needs 482 W, at intensity from 16 to 520 times AM0 ( $700 \text{ kW/m}^2$ )
    - Intensity varies by factor of 32
    - Temperature varies by factor of  $32^{1/4} = 2.4$
  - *Requires radiator*





Thermal conversion simplified block diagram

Absorber



Thermal  
input

A heat engine runs off a temperature differential between hot and cold sides

**Needs a radiator**

Radiator

Heat engine

Electric power out

Pumped coolant loop sends waste heat to radiator





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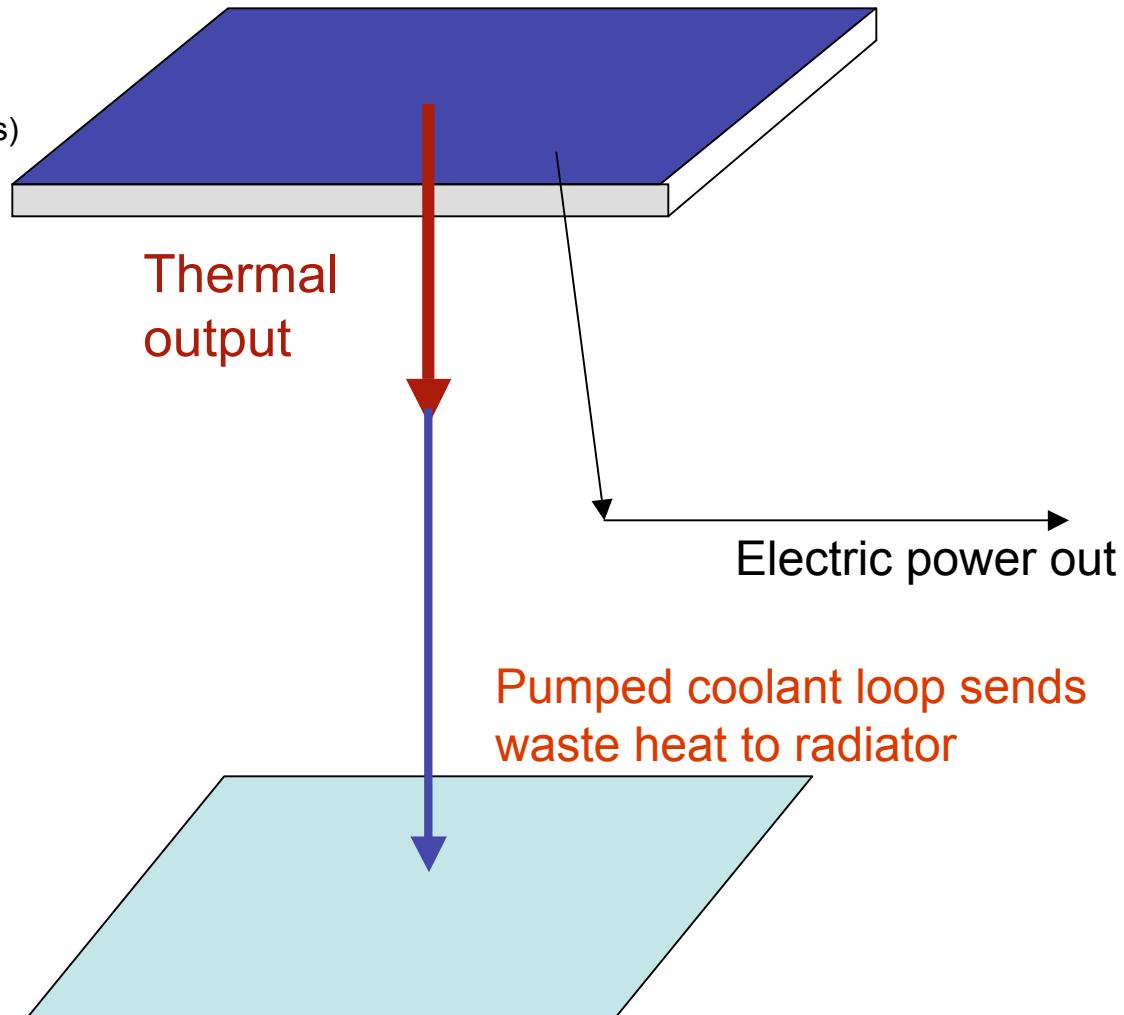
## PV array

(high efficiency concentrator cells)

## Radiator



Cooled PV simplified block diagram





## Radiator comparison: PV vs Stirling

- Thermal/Stirling conversion:
  - Sunpower ASRG converter efficiency 36% demonstrated
    - Must operate over high dynamic range of input
      - Hot-side Temp (.25 AU, coldest case) ~788 K
      - 36% efficiency requires cold side at 315K\*
      - 28% efficiency requires cold side at 420K\*
      - Assumes hot-side temperature not drawn down by power system
    - No help from spectral selective coatings
  - PV:
    - Pumped coolant loop keeps temperature < 120°C (393K)
    - Baseline concentrator cell efficiency 35% at AM1.5
    - extrapolates to **28% AM0 efficiency** at 120°C operating temp
    - Efficiency increases if spectral selective coatings are added

Roughly comparable in temperature, efficiency and radiator area

\* Assumes Efficiency= 60% of Carnot

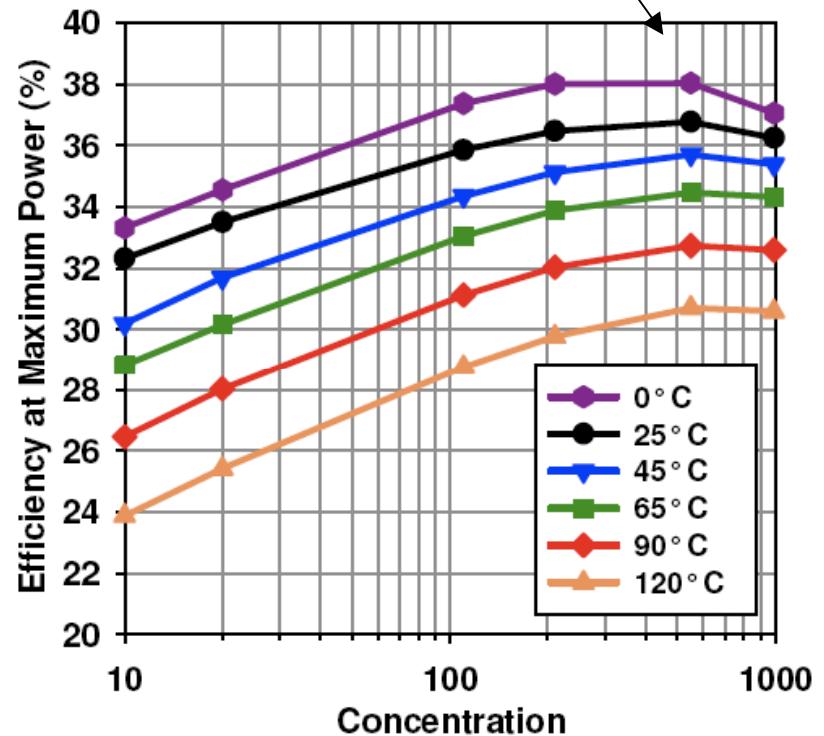
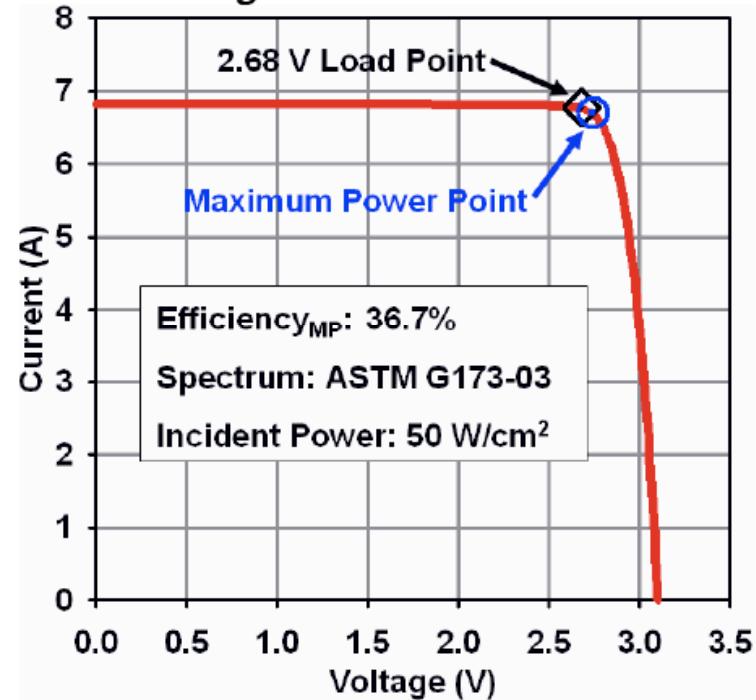


## Concentrator PV Cell Specs



Effective concentration at 9 solar radii

**Current-Voltage Characteristic**



Cells available now from  
Spectrolab or Emcore

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Note: AM1.5 spectrum quoted, not AM0

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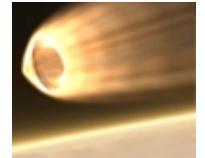


## Design

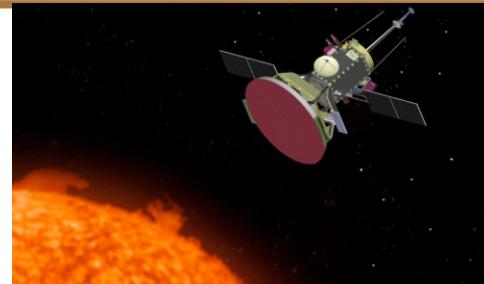
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- Primary array folds away behind shield at distances inside 0.25 AU
- Secondary solar array will use concentrator solar cells cooled by pumped liquid coolant circulating to radiator
- Secondary array used at solar intensity 16 to 250 suns
- Pumped cooling loop keeps maximum temperature to <120°C





## Power Variation with distance from Sun



**Incident power varies with distance from sun  
Intensity varies by factor of 32**

Array sized for 482 W at 0.25AU

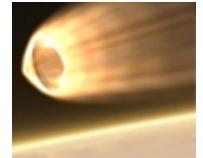
Main size (cost) driver is the cooling radiators that keep the high-intensity array cool

Radiators are oversized at 0.25 AU

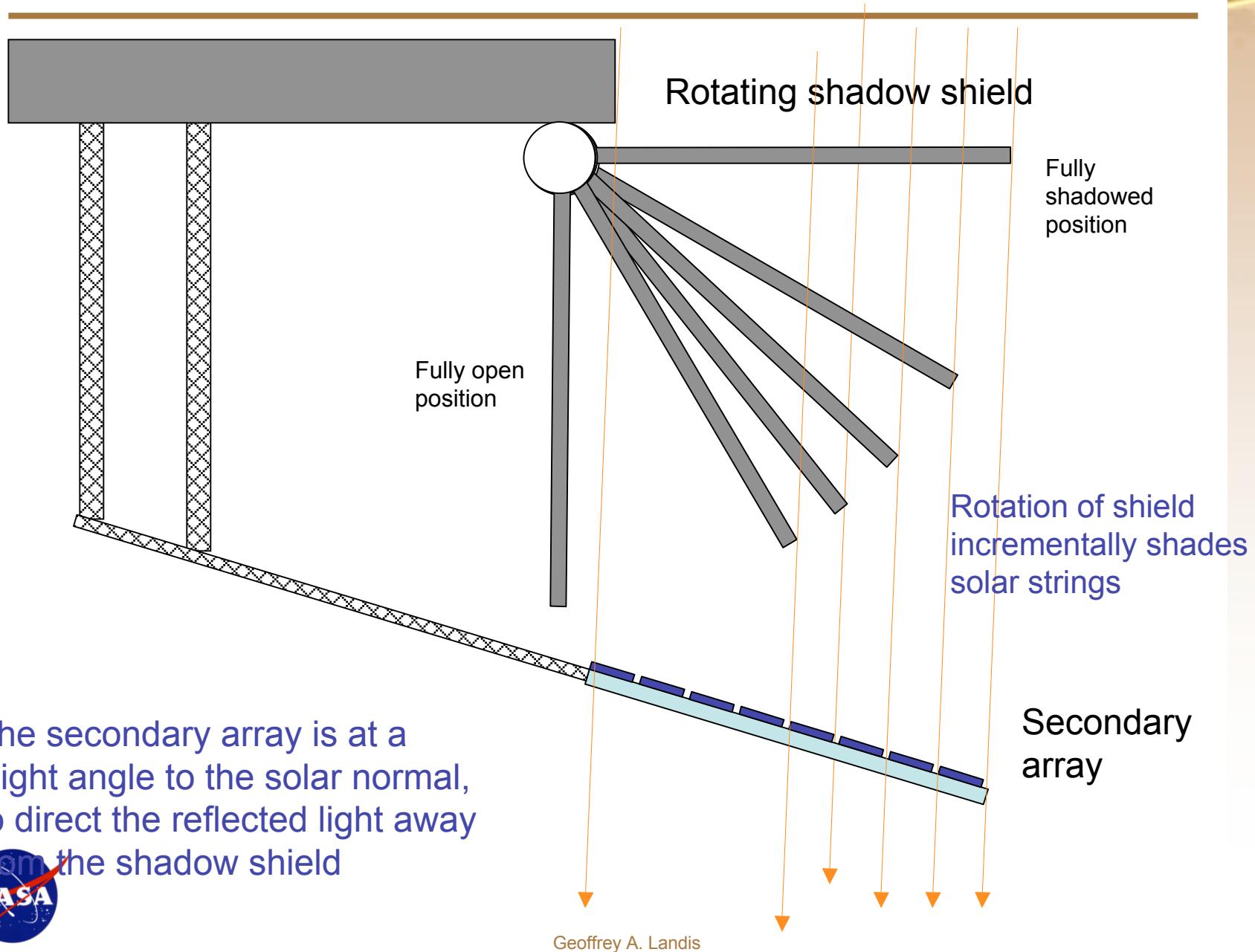
**Array is oversized at perihelion**

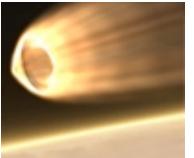
At closest approach (9.5 Rs), the secondary array panels require a total equivalent cell area of 34.04 cm<sup>2</sup>





Many Approaches Considered  
Rotational joint for shadow shield





## Many Approaches Considered

Rotational joint for secondary array

### Thermal (shadow) shield

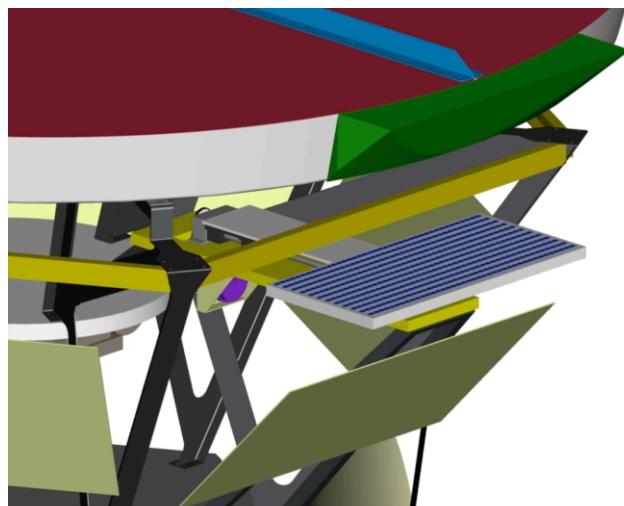
This approach combines off-pointing and progressive shadowing

### Secondary array

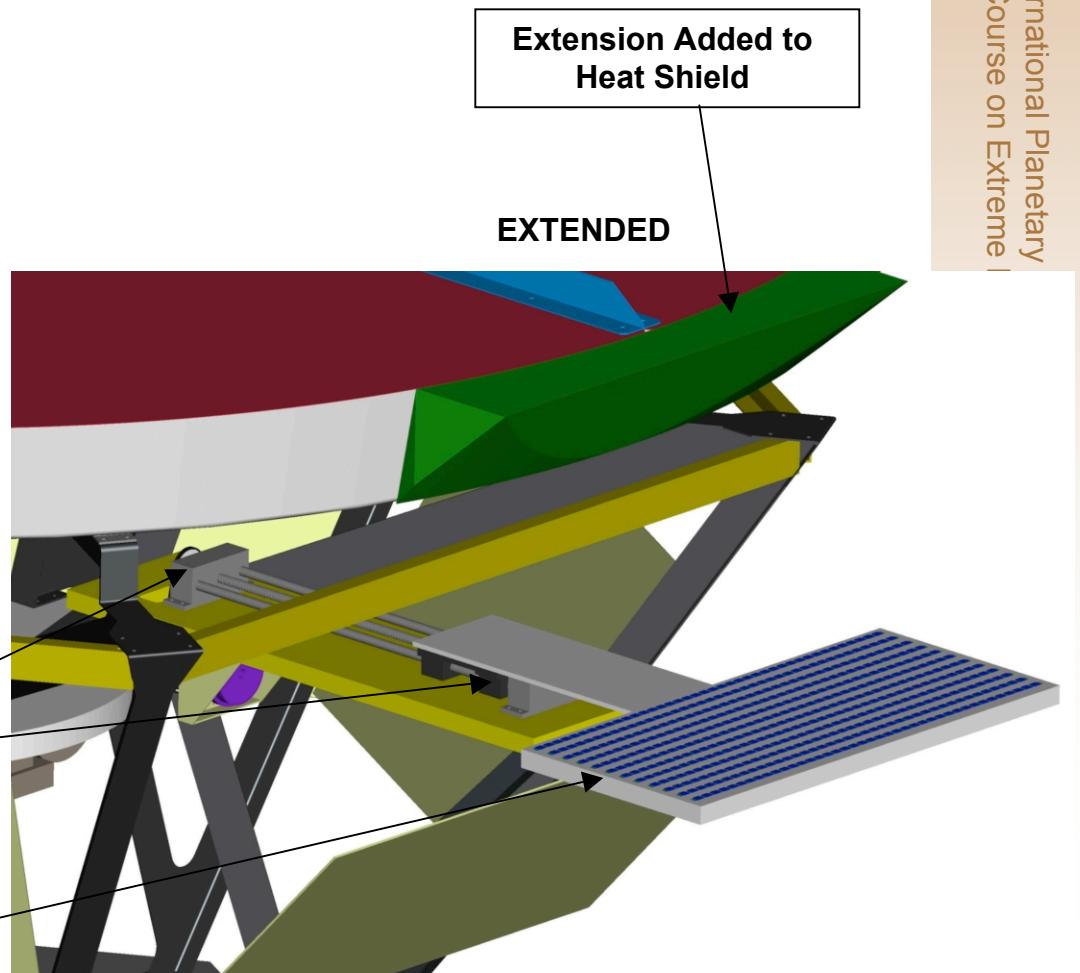
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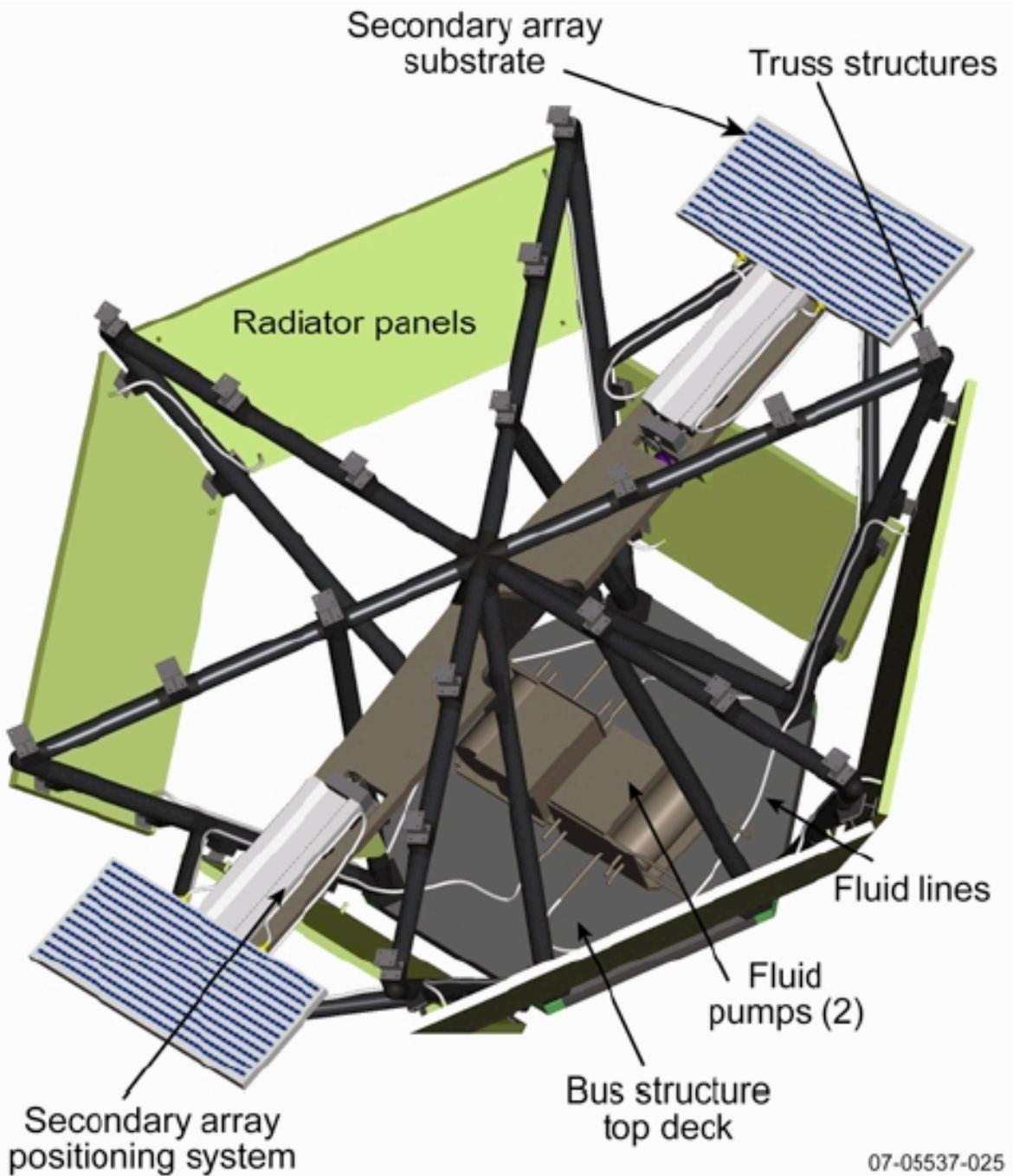


## Final design: Knife-edge shield for secondary Solar Array



RETRACTED





07-05537-025

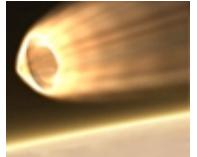
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## Interior detail

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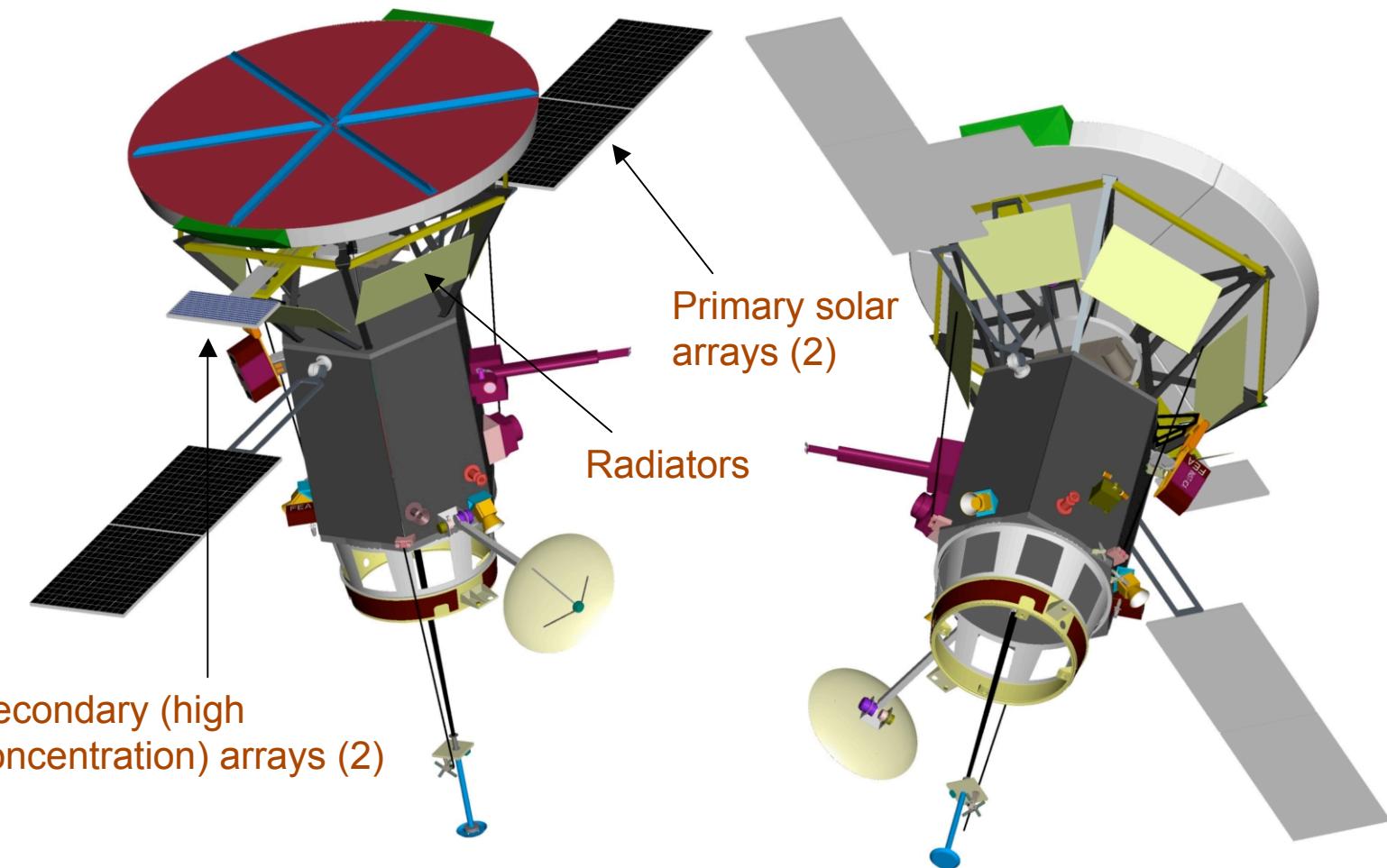
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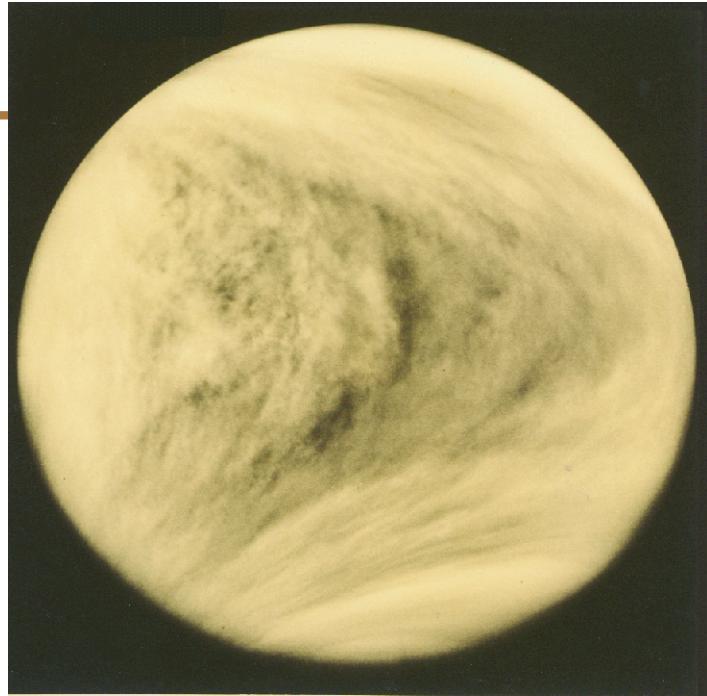
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## Venus: A Challenge for Exploration

- Solar day 117 days
- Surface temperature 452 C (850F)
- Tops of mountains are slightly cooler: at the top of Maxwell Montes (10.4 km above mean elevation), temperature is “only” 390 C (725 F)
- Surface pressure 92 bars (equals pressure 1-km under the ocean) carbon dioxide
- Clouds are concentrated sulfuric acid droplets



Venus in the UV (viewed from the Pioneer Venus orbiter)

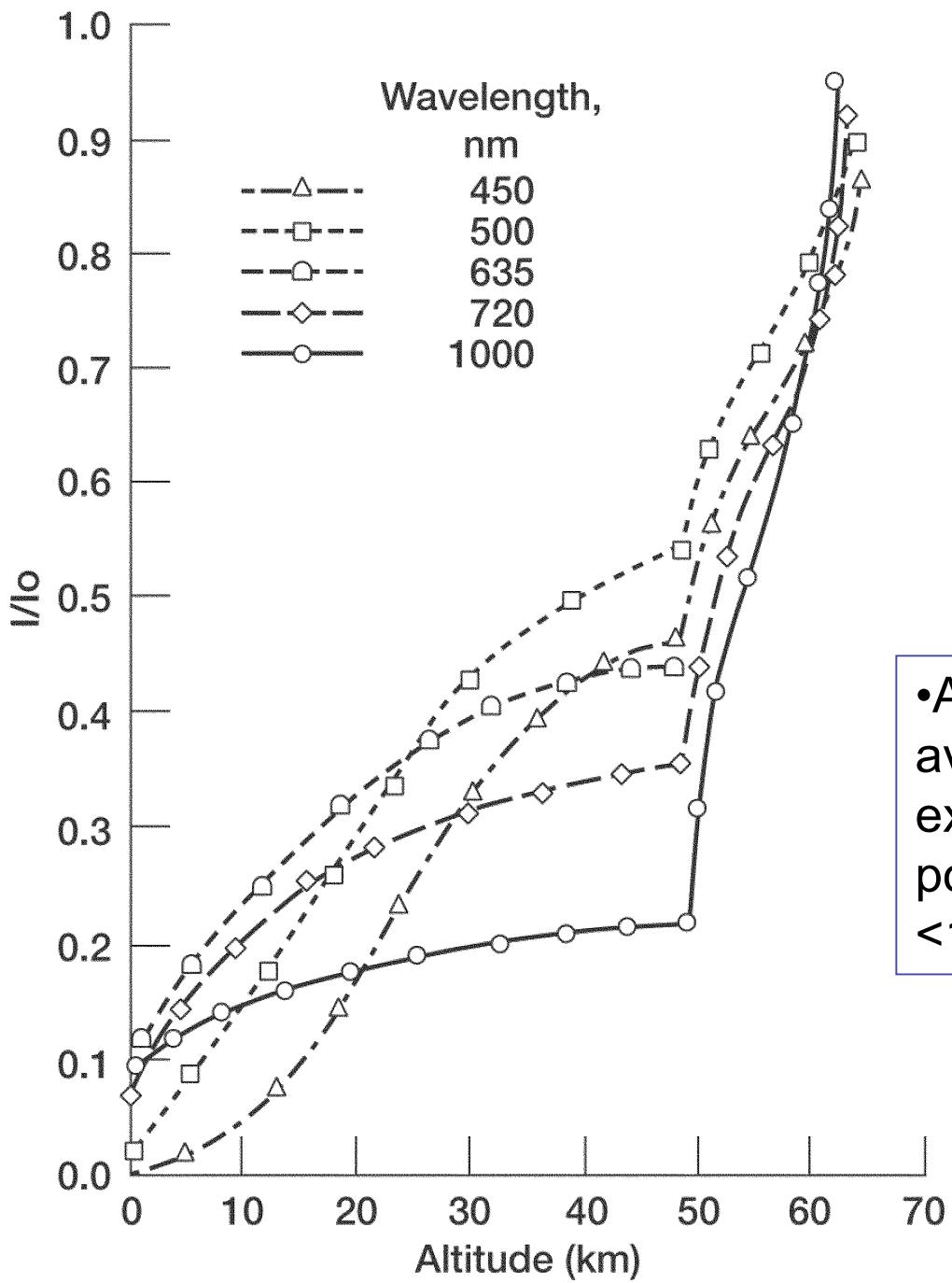


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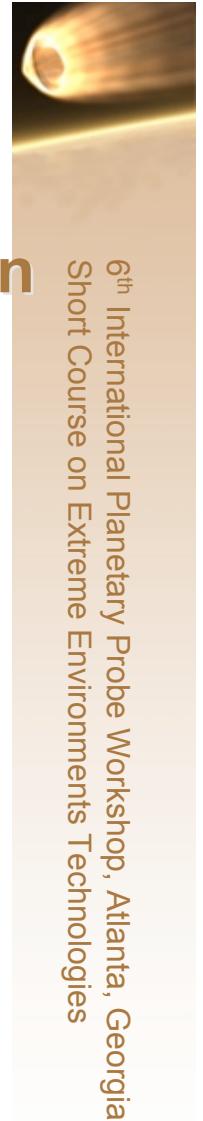
**Venus Exploration is a tough challenge!**





## Solar energy in the Venus atmosphere

- At surface,  $I/I_0$  available is 10% of exoatmospheric power at 1000 nm, <1% at 450 nm



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# Venus lower atmospheric exploration: Balloons

Main problem: envelope material for operation

## Envelope materials:

- Flexible:
  - woven carbon fiber cloth (high temperature mechanical strength)
  - Polyimide material (gas containment)
    - High T polyimides lose strength at  $T > \sim 350^\circ\text{C}$
  - Corrosion barrier (to prevent chemical attack)
    - Two layer gold /  $\text{SiO}_2$

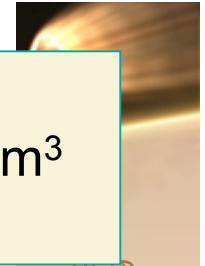


## •Rigid:

- Titanium sphere for strength to weight ratio & thermal performance
- $P(\text{interior})=P(\text{exterior})$  at mission altitude ("zero pressure balloon")
- Corrosion barrier prevents chemical attack
  - Two layer:  $\text{TiO}_2$  plus  $\text{SiO}_2$
- Spherical entry shell at low ballistic coefficient: good entry dynamics
- Launch limitation: diameter < 3.8 meters (Delta-IV 4-m shroud\*)

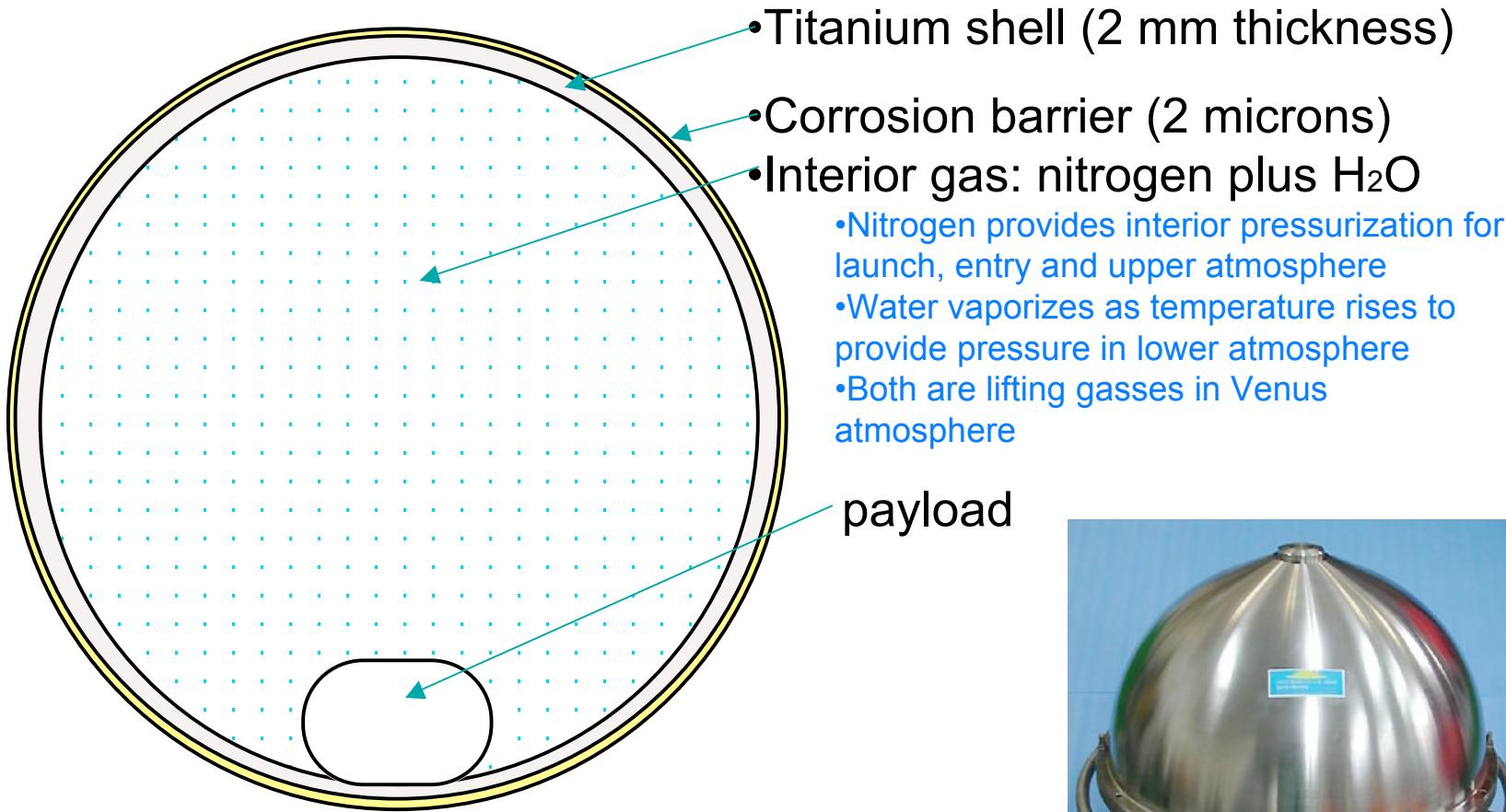
»\* (4.8 meter if Delta-IV Medium-plus or Heavy is used)





## Conceptual titanium-shell balloon

- Target altitude 5 km
- Atmospheric density 50 kg/m<sup>3</sup>
- Temperature 425°C



Titanium sphere (Kayo Denshi Inc.)

Geoffrey A. Landis

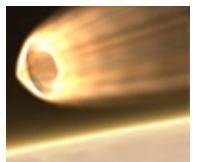


## Salyut 7/Kosmos 1686 Helium Tank after Earth reentry



<http://fernlea.tripod.com/s2.jpg>

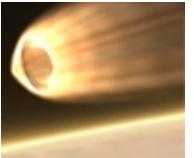
- 14 inch diameter titanium sphere
- Ablation marks are primarily from other parts of spacecraft ablating away



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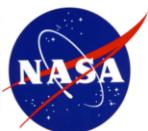
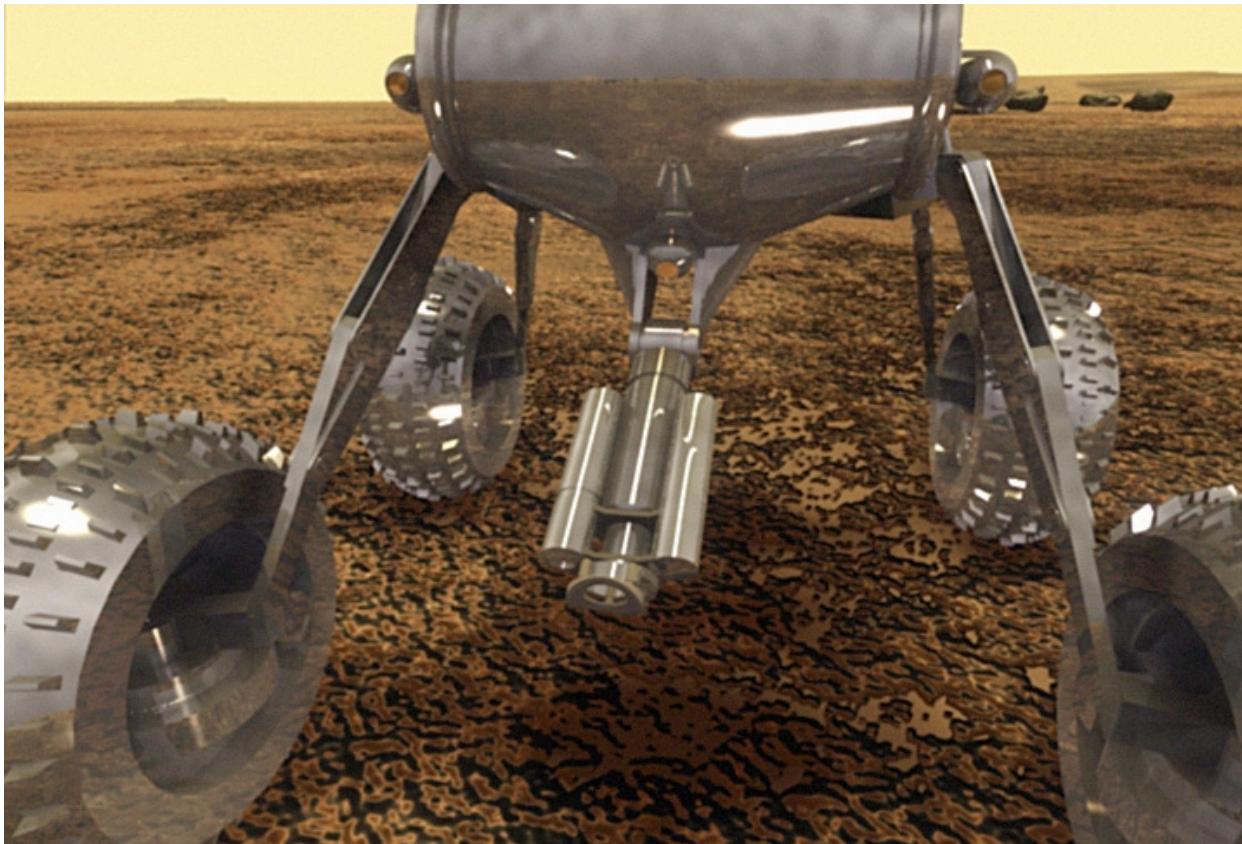
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## Refrigerator to keep electronics at low temperature

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- Requires power and moving parts
- Allows existing electronics

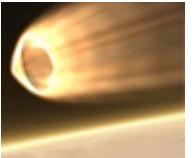




## Cooling options

Thermoelectric (Peltier)	Not available at Venus temperatures; needs technology development
Reverse Brayton	High speed turbomachinery as is currently operating on Hubble Space Telescope
Free-Piston Stirling	Rotating or free piston linear configurations are possible Space experience: Cryocoolers currently operating on NASA spacecraft
Thermo-Acoustic Stirling	Eliminates the need for a displacer Space experience operating on NASA/DOD/NOAA spacecraft
Multi-stage Rankine/Brayton	High speed turbomachinery, high temperature motors Requires staging integrated into design

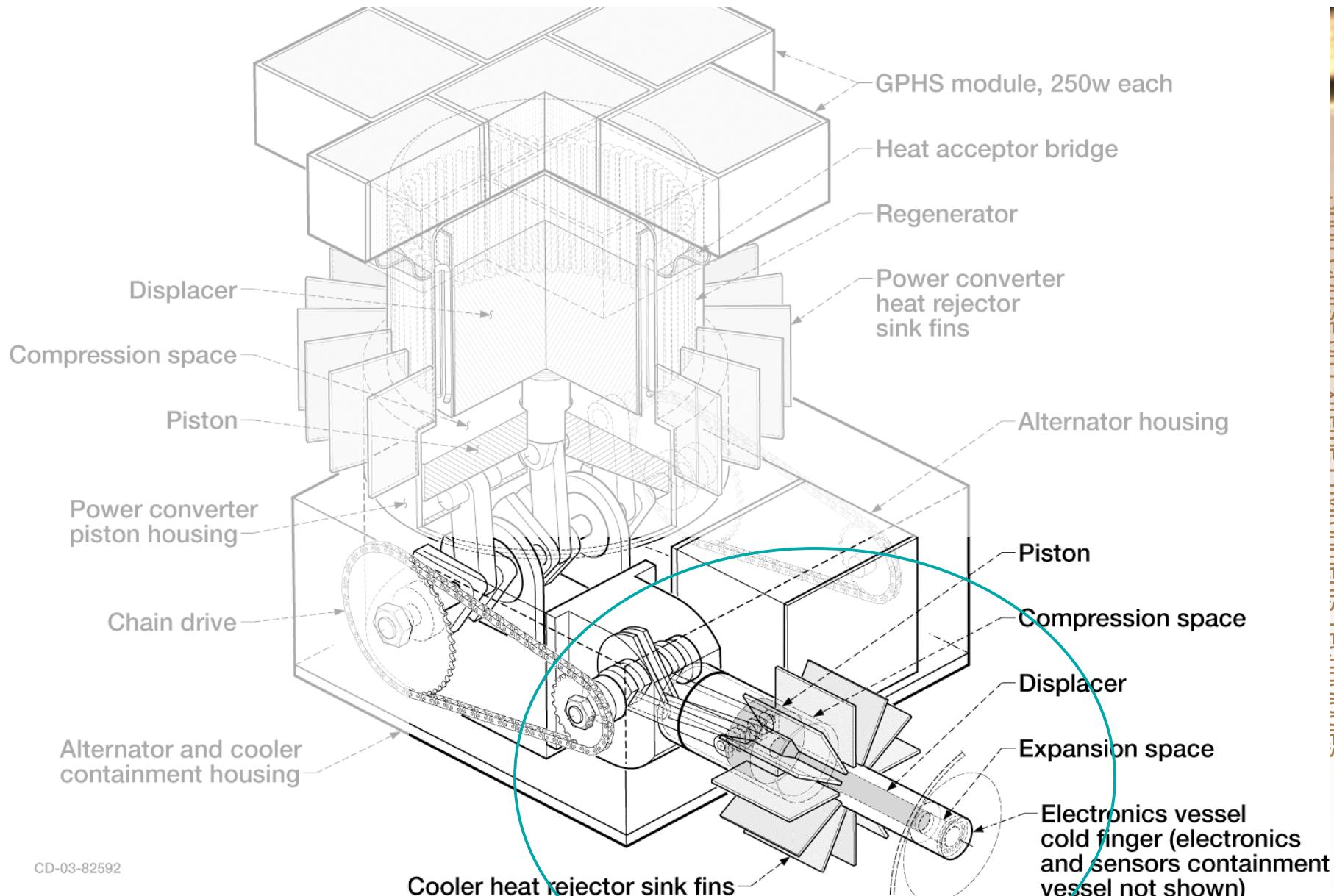




## Venus Surface cooling system

Parameter	Value
Type	Stirling cycle
Stages	1
Heat sink temperature	500 C
Cold temperature	200C
Heat transferred	105.7 W
Heat rejected	344.6 W
Overall coefficient of performance	37.6%
Mass	1.6 kg





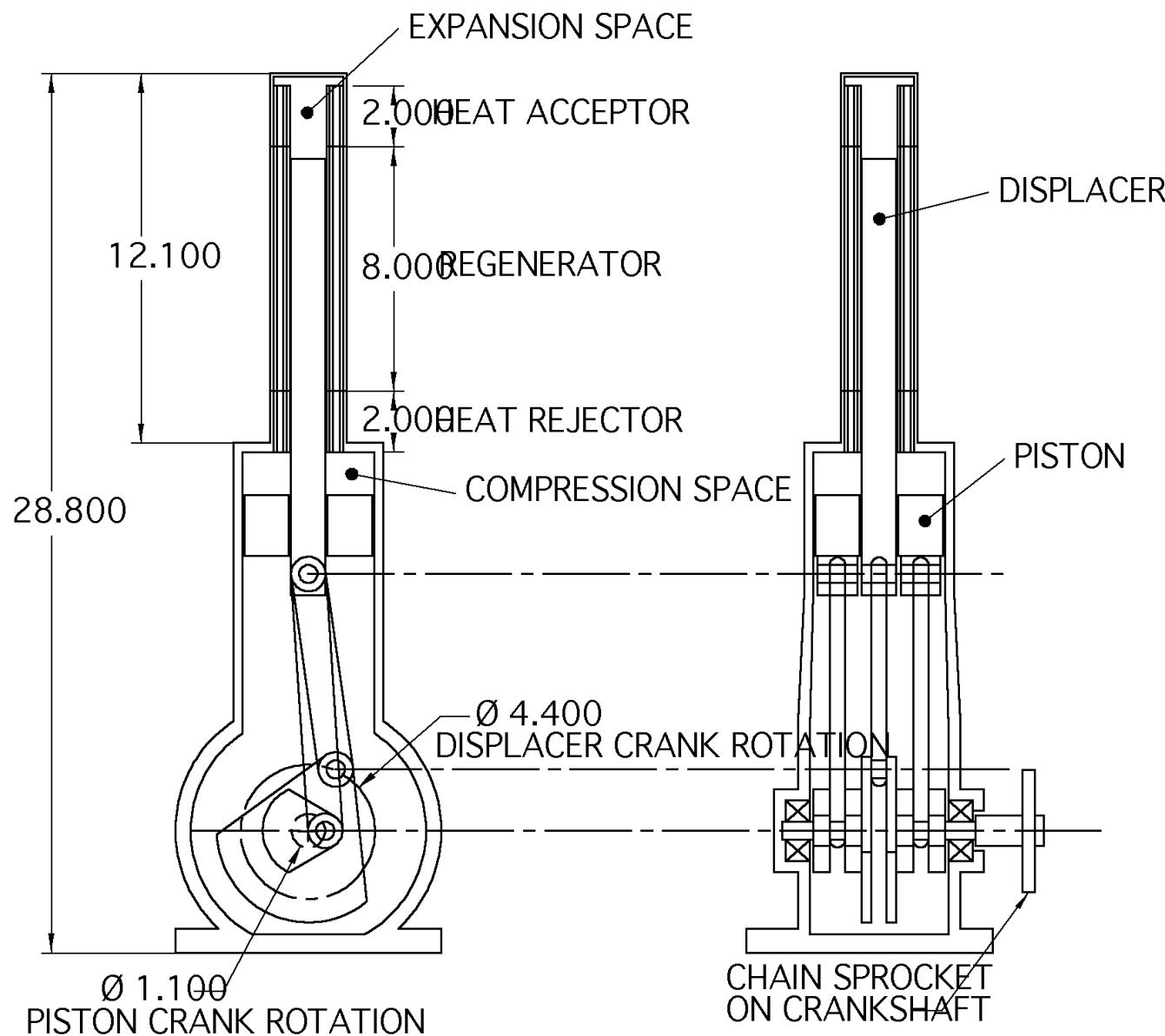
## Sterling cooler design





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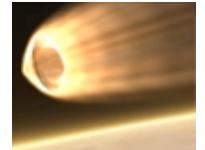


## Stirling Cooler for the Venus Surface



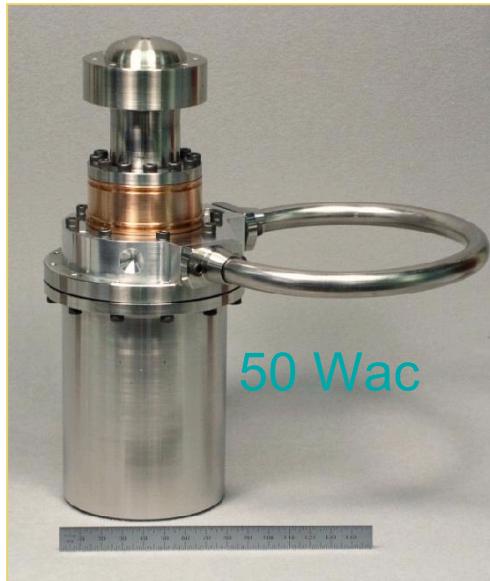
Geoffrey A. Landis

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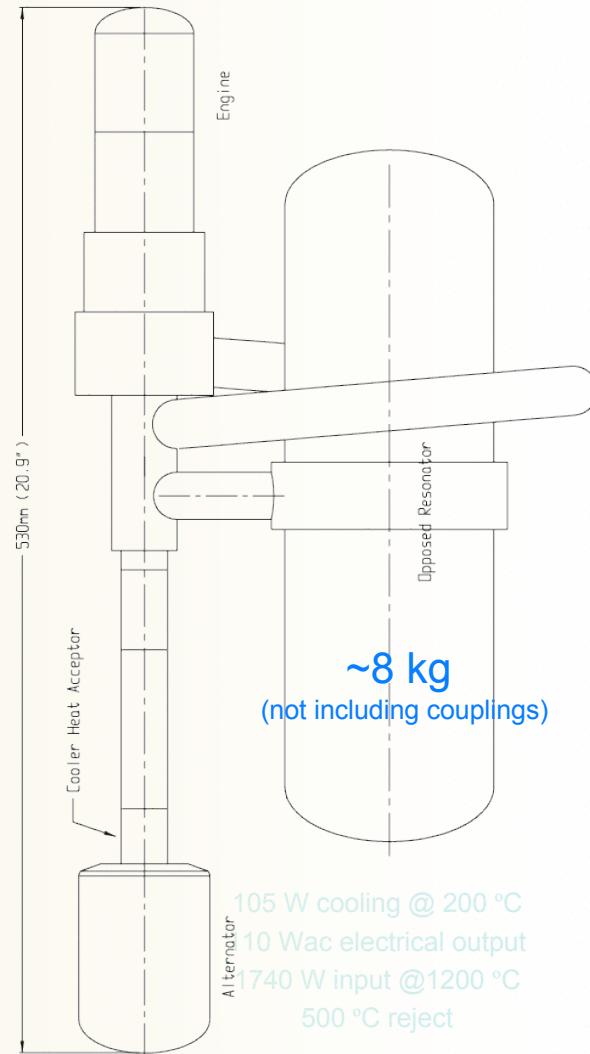
## Single GPHS Sunpower TASHE, 2008 cooler plus power source

- Sunpower design is coaxial with heat exchangers surrounding the Thermal Buffer Tube
- Sunpower convertor performance is presently equal to Northrop Grumman
- Predicting 65 Wac,
  - 8 months development remaining in SBIR
- Design and evaluation for higher power is part of the current SBIR



50 Wac

### Venus Duplex



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### Comparison of Northrop Grumman & Sunpower Technology



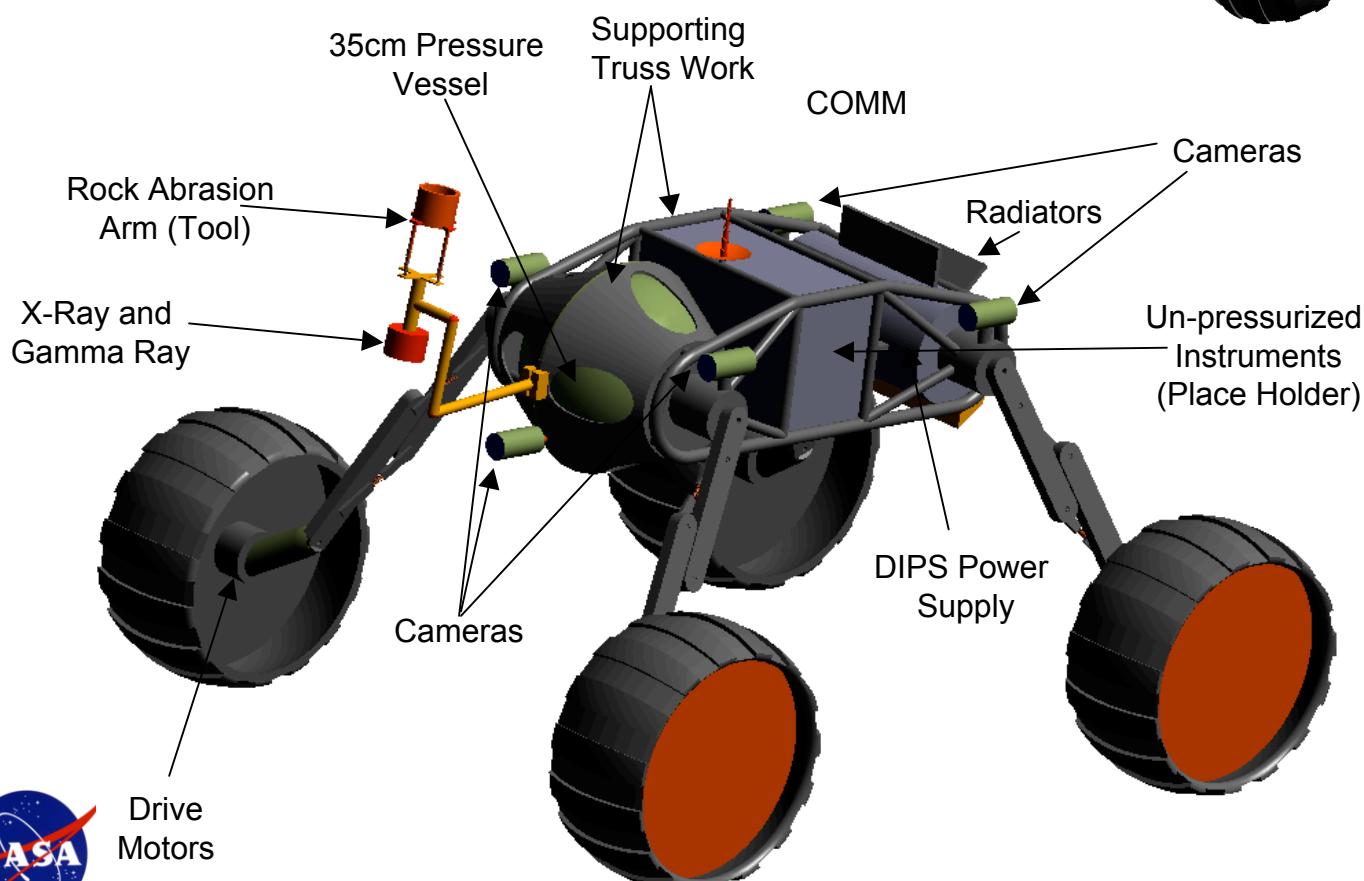
Northrop Grumman



Sunpower

	Sunpower	Northrop Grumman
Pressure	3.65 MPa (530 psia)	5.28 MPa (765 psia)
Frequency	100 Hz.	125 Hz.

# Surface Rover concept



Seismometer Deployment

Wheel Deployment  
Parallelogram Concept

Planetary Probe Workshop, Atlanta, Georgia  
Extreme Environments Technologies

CAD model by  
Shawn Krizan,  
NASA LaRC

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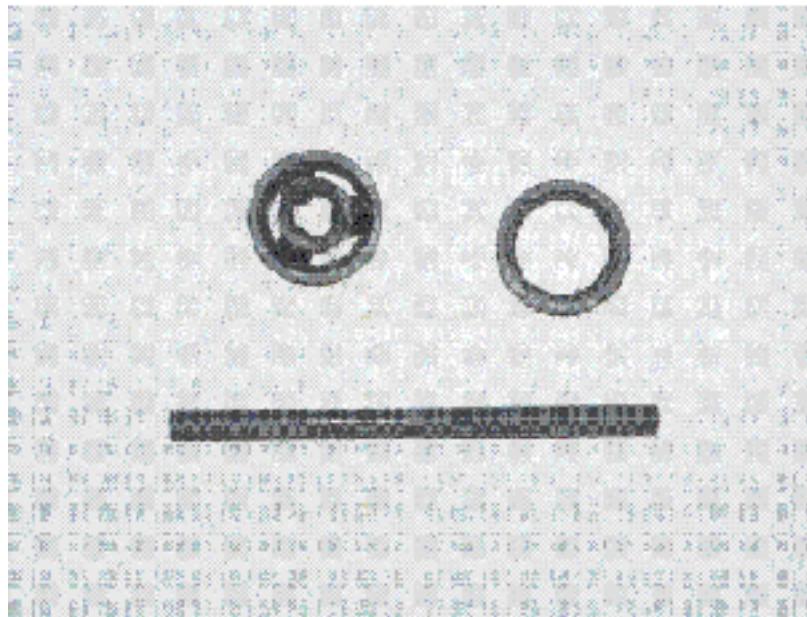


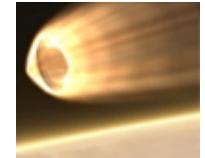
# High-temperature Si<sub>3</sub>N<sub>4</sub> bearings

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## AFRL high-temperature ceramic bearings

- Silicon nitride bearing
- Cesium silicide lubricant
- Tested to 1250 F (675 C) for 50 hours





# Venus Surface Robot Technologies:

## High temperature Motor design issues

### Approaches

- High temperature permanent magnets
  - (1) Motor design using no permanent magnets
  - (2) High temperature magnet materials (Alnico, high temperature SmCo)
  - (3) Cooled magnets
- High temperature insulation
  - (1) Ceramic or ceramic-filled high-temp silicones
- High temperature bearings
  - (1) Magnetic bearings
  - (2) High temperature lubricant
- Control electronics
  - (1) SiC electronics
- Wire resistance
  - (1) Ceramic or ceramic-filled high-temp silicones
- Power-system start-up transient
  - (1) May require battery buffering





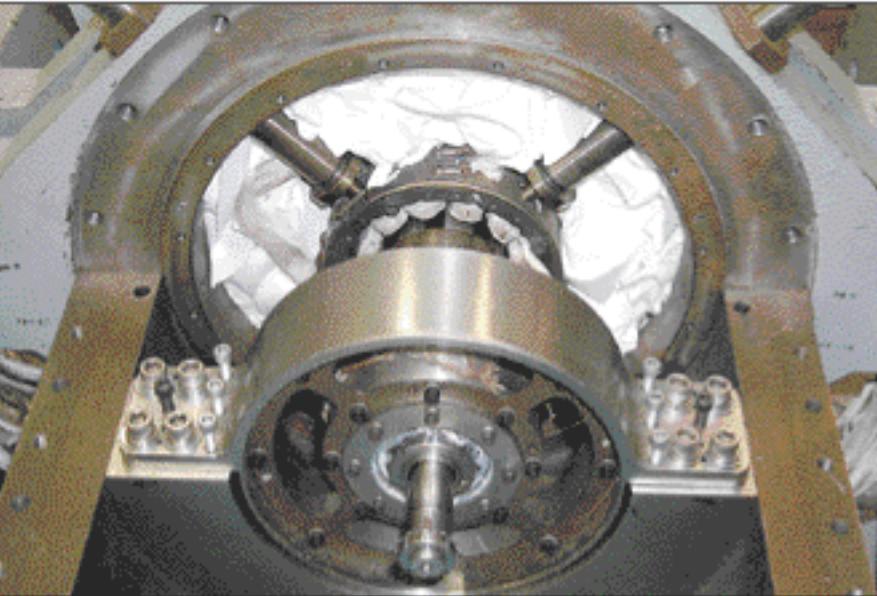
# Venus Surface Robot Technologies:

## motors and actuators

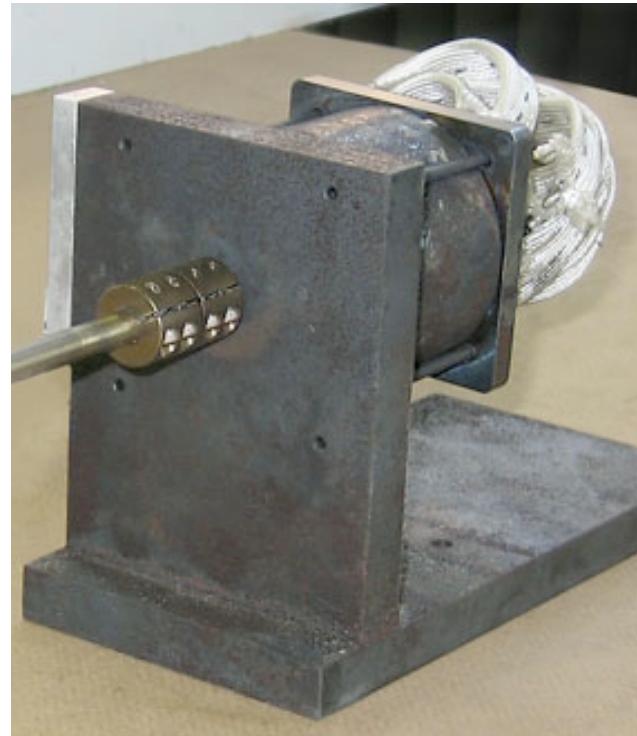
Motor or actuator	Max operating temperature ( C )	status
Baker Hughes GeoThermal	160	Commercial motor for drill app.
Swagelock pneumatic	200	commercial
Rockwell Scientific SiC	200	development project
NASA Glenn switched-reluctance motor	540	demonstrated; 8000 RPM, 27 hours
Honeybee robotics	460	Prototype motor for Venus
General Electric research	725	Synchronous AC motor "highest ever temperature for a motor"
U. Sheffield Linear actuator	800	technology demonstrator: 1 mm throw, 500N force
NASA Glenn/MSU RAC smart materials: Shape memory alloy actuators	150 500 1000	Shape memory (SMA): commercial SMA: material demonstrated SMA: high temperature goal



# NASA GRC Switched-reluctance motor capable of operation at 540 C



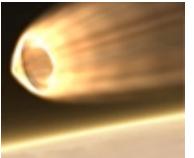
Montague, Gerald, *et al.*: High-Temperature  
Switched-Reluctance Electric Motor, *NASA Tech  
Briefs*, vol. 27, no. 2, 2003.



Honeybee Robotics implementation  
of switched-reluctance motor, tested  
at Venus temperature and pressure

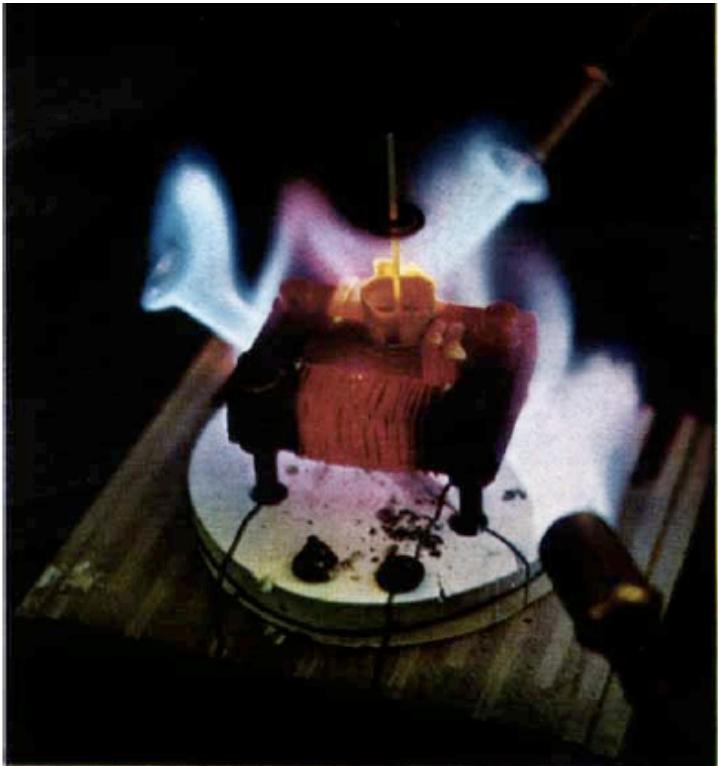
<http://www.honeybeerobotics.com/high-temperature.html>





## Other high temperature motors

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General  
Electric 1971:

*The high temperature motor developed by General Electric in operation at about 700°C. The motor is being heated by three oxygen/gas torches. The field windings made of 0.030 in. NiO-clad silver-palladium wire form a coil of 24 turns round the field pole-piece laminations.*

GE High temperature motor shown being heated with three blowtorches

<http://www.platinummetalsreview.com/pdf/pmr-v15-i3-100-101.pdf>

Platinum Metals Rev., 1971, 15, (3), pp. 100-101



# Power source

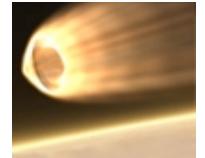
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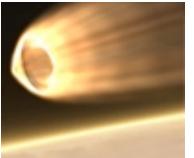
## Venus Surface power source:

### Solar power

Three effects decrease the efficiency of solar power

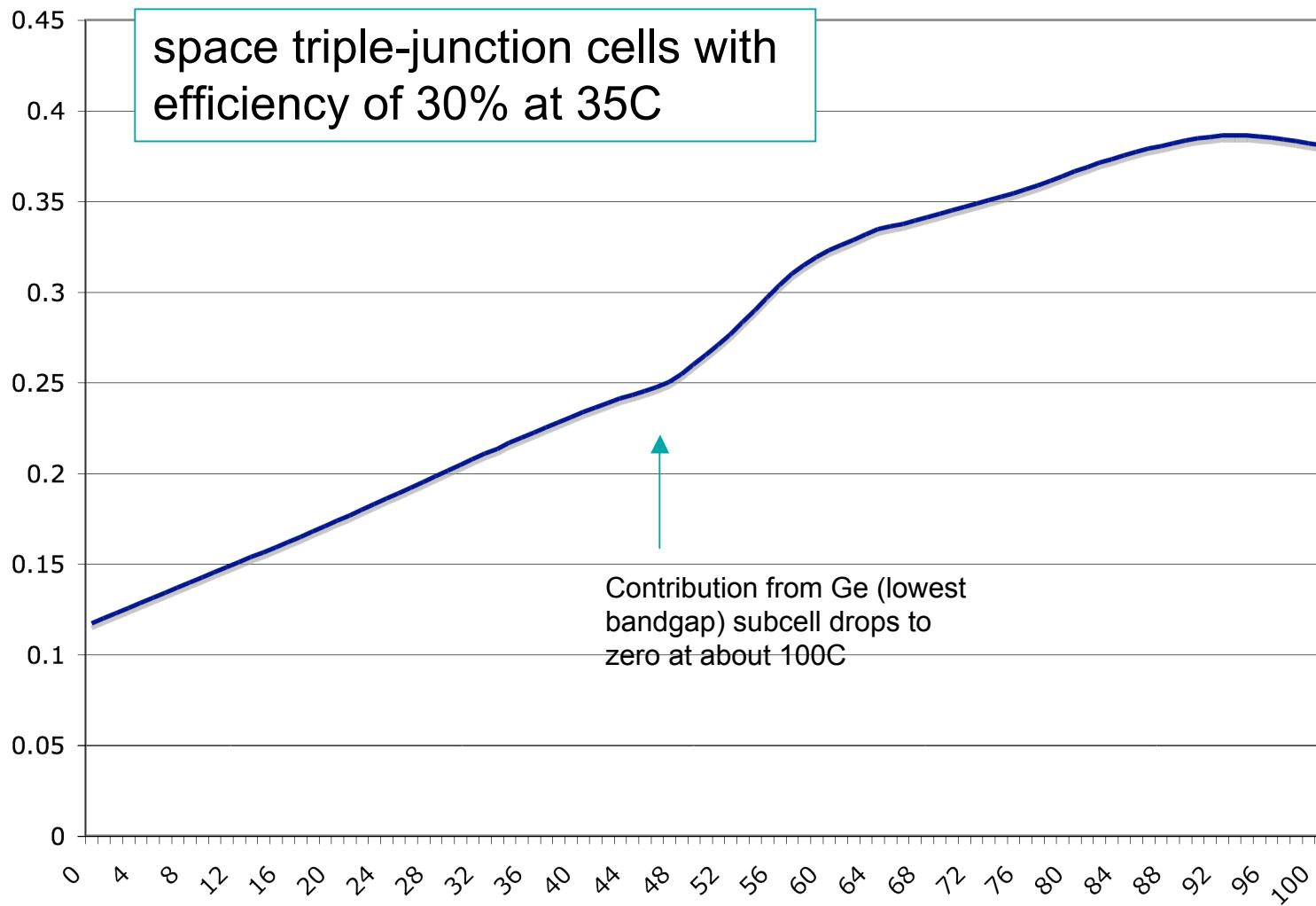
- High temperature at surface
  - Solar cell efficiency decreases with temperature
  - New high-temperature solar technologies are most sensitive to blue light
- Low light levels at surface
- Spectrum shifts due to Rayleigh scattering





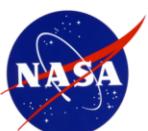
# Solar Power

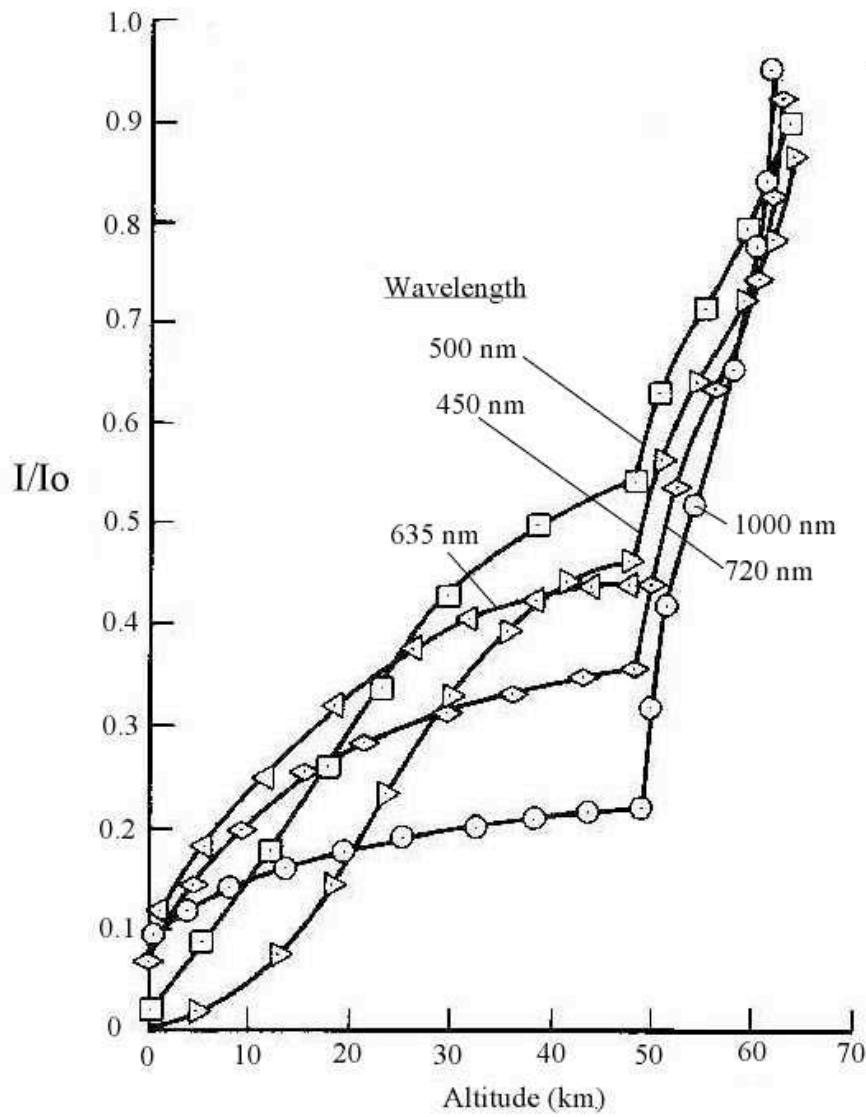
**Estimated thermal effect of Venus atmosphere on solar cell efficiency  
(does not include effect of spectral change)**



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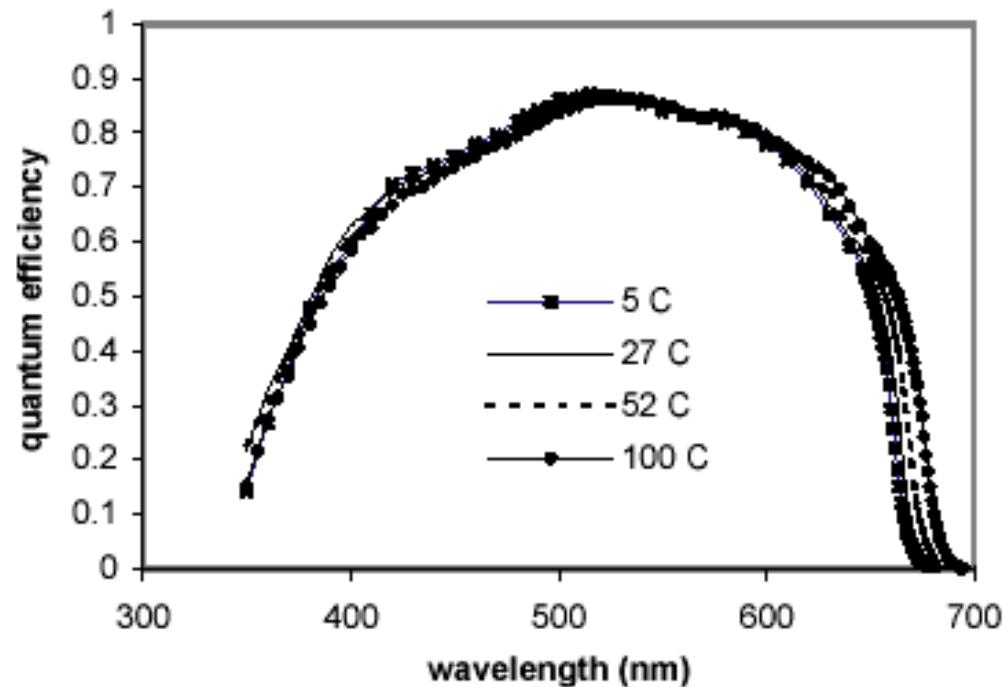
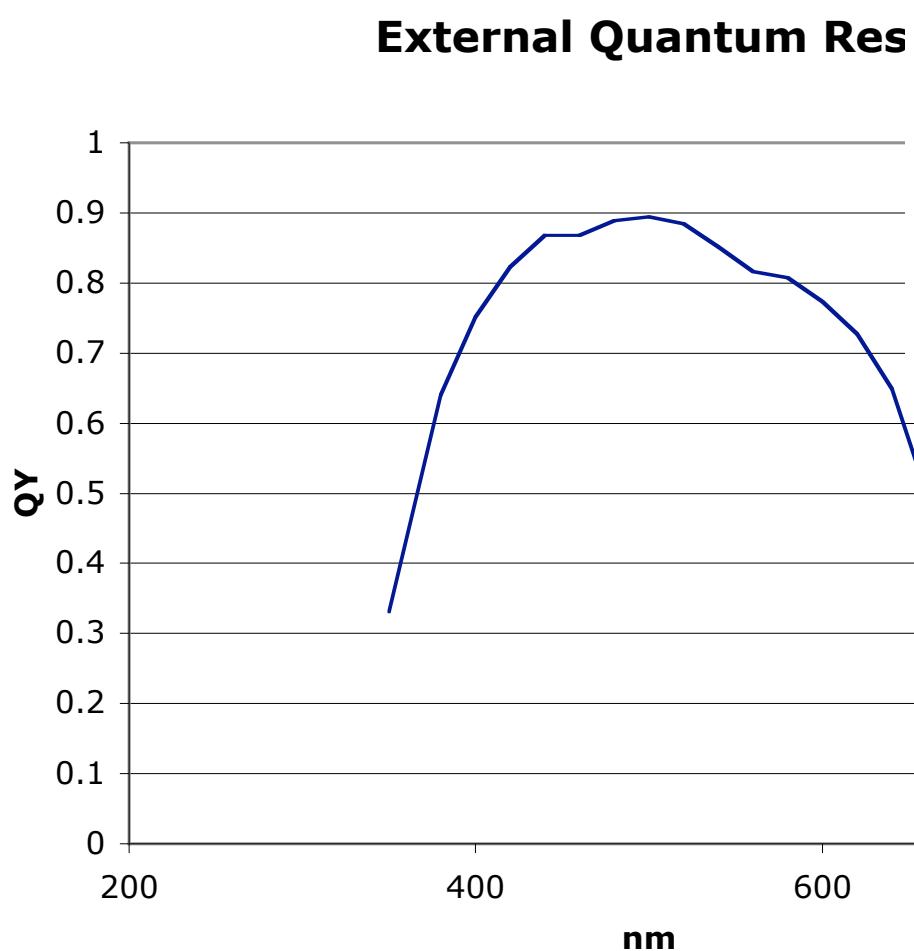




Data from Venera-11 descent probe  
(from NASA SP-461, p. 177, 1983)



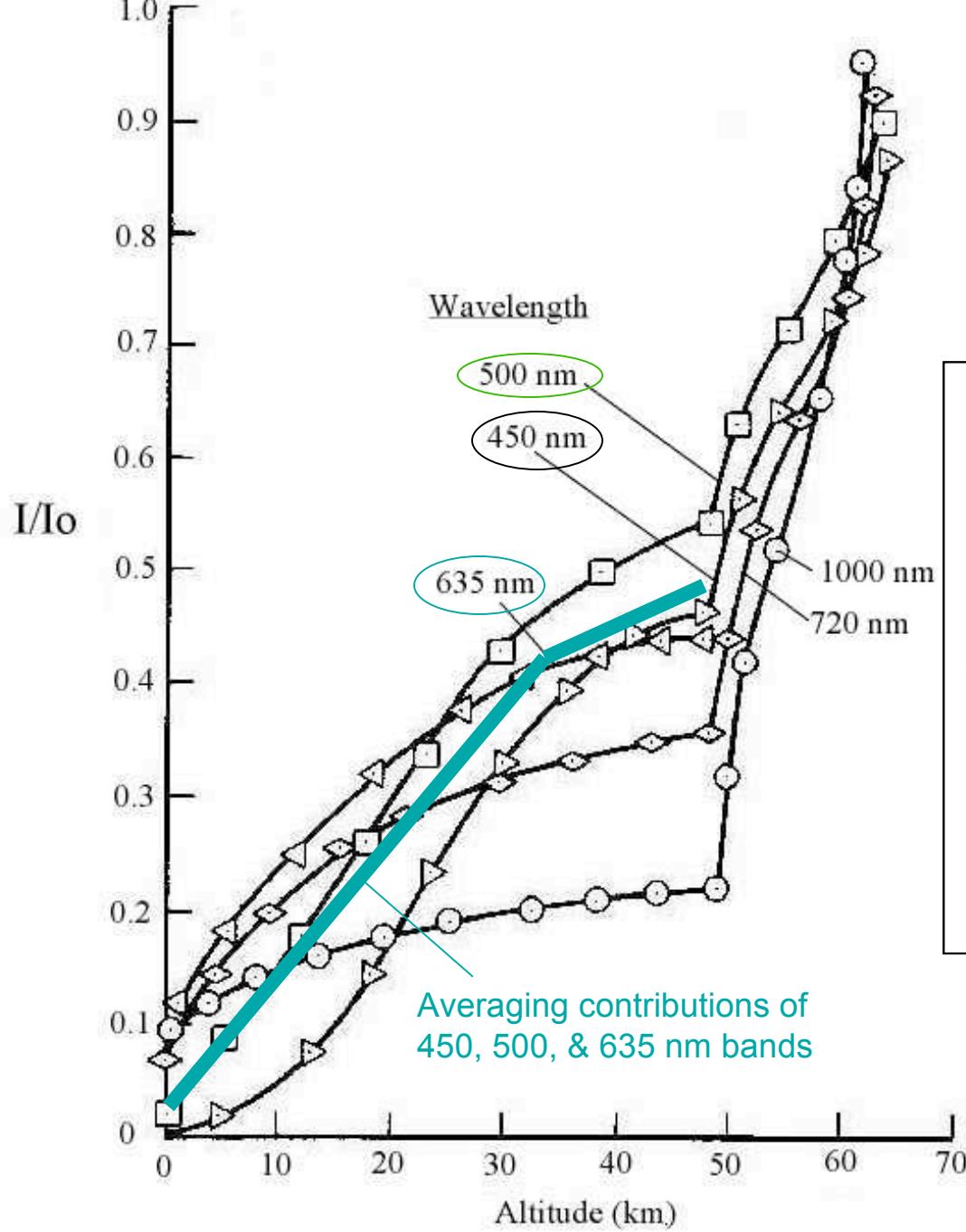
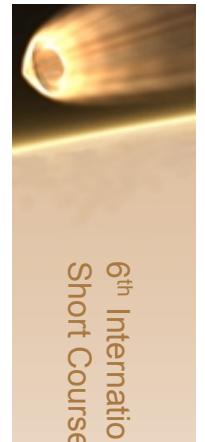
## Spectrum effect on top (blue) cell



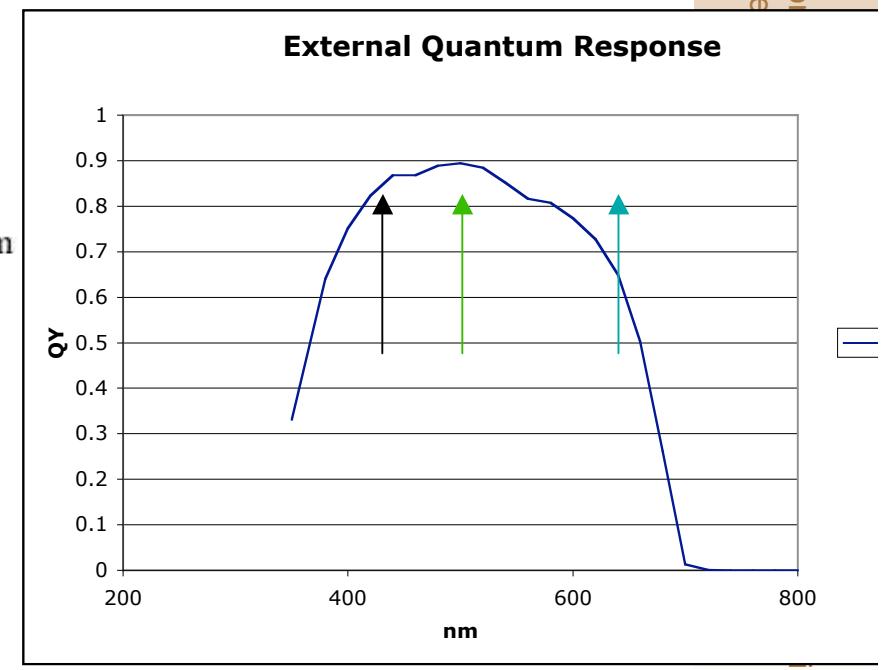
Response shifts  
slightly toward red  
as cell gets hotter



# Spectrum and intensity



Data from Venera-11 descent probe  
(from NASA SP-461, p. 177, 1983)



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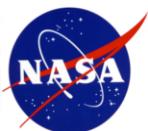


## Venus Surface power source

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### Chemical power

- Battery or fuel cell
  - Good for prime power for short mission
  - For long mission, storage of reactants needed becomes critical
  - Needed for power buffering for isotope power systems



# High temperature Battery choice: Na/S

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## Sodium sulfur batteries

- Well demonstrated on Earth; commercial production
  - Invented by Ford
  - Powered Ford "Ecostar" demonstration vehicle in 1991.
    - Uses today are for utility-scale electric power buffering
  - High efficiency rechargeable battery
    - better power density, lower self-discharge than lithium cells
  - Prototype NaS battery demonstrated on space shuttle
  - Typical operating temperature for terrestrial applications is 290-390C
    - Maximum temperature is limited by the boiling point of sulfur
      - At Venus pressure of 92 bar, sulfur is liquid at 460C.
  - Other thermal battery technologies exist (Na/FeCl, etc.)



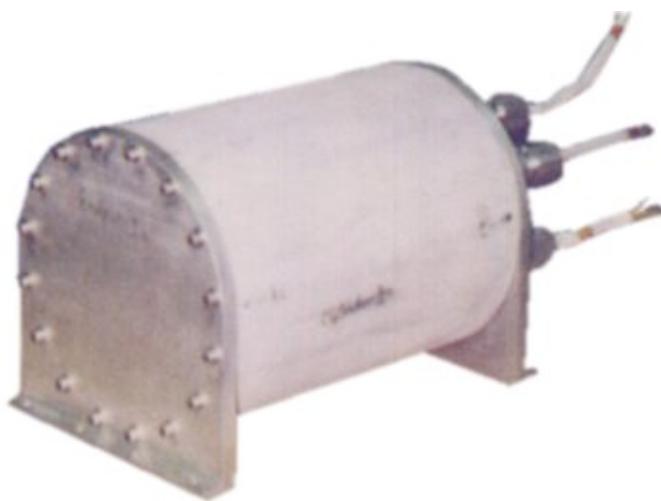
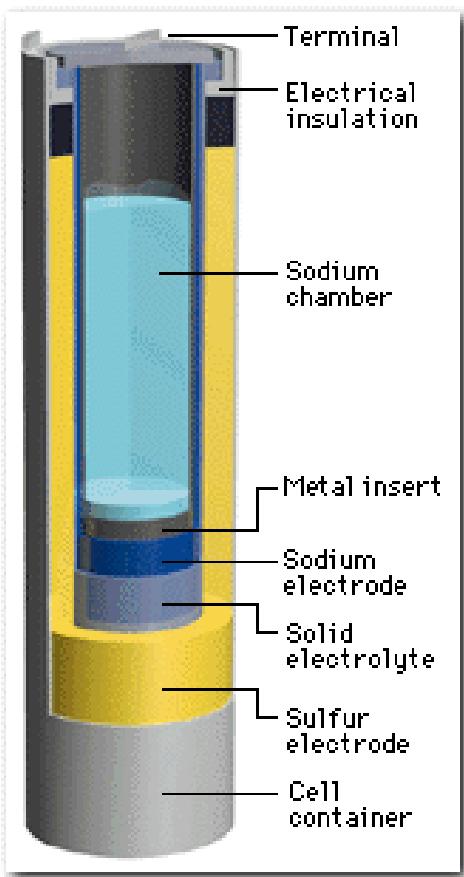


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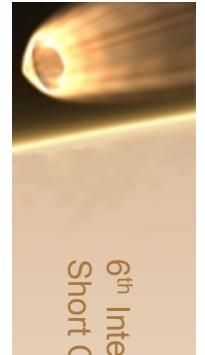
# Sodium Sulfur battery



Sodium sulfur battery  
flown on shuttle in 1997

Sodium sulfur battery  
schematic

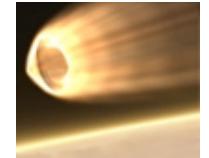




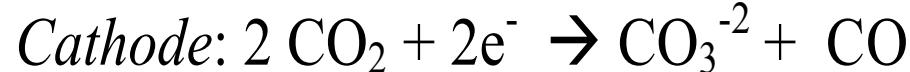
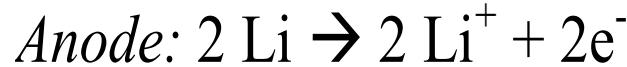
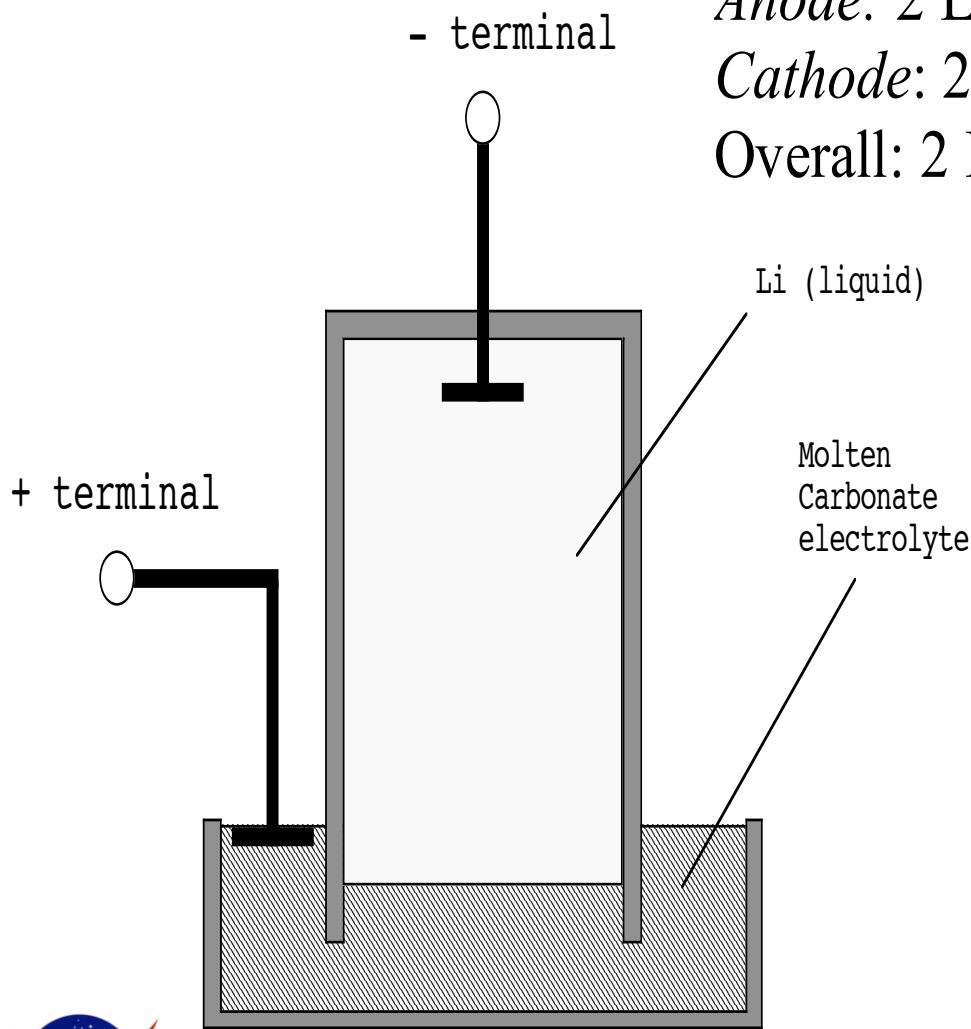
## Proposed primary battery technology: Li/CO<sub>3</sub>

- A New Battery design to use Venus resources
  - *Uses carbon dioxide from Venus atmosphere as reactant*
  - *Theoretically much higher specific power*
- Based on molten carbonate fuel cell technology
  - *Technology well developed for fuel cells*
  - *Operating temperature comparable to Venus surface*
- Technology readiness level is low
  - *TRL 3*
  - *Not useful for applications other than Venus*
  - *Simple chemistry- no known showstoppers*



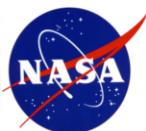


## Proposed Na/CO<sub>3</sub> battery



### Electrolyte:

- ternary eutectic carbonate  
 $(\text{Li}_{0.44}\text{Na}_{0.30}\text{K}_{0.26})_2\text{CO}_3$
- melting point 393 C
- Molten chloride eutectic electrolytes also possible





## Venus Surface power source selected

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- **Radioisotope Power source**

- Although 460 C is a higher heat rejection temperature than most dynamic conversion approaches, should be possible
- Long history in planetary exploration
- Dynamic or thermoelectric conversion approaches possible
- **Baseline technology chosen for the Venus rover**



# Studies of Venus Radioisotope Stirling Power systems:



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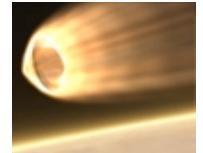
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Study	M(kg)	P(W)*	T <sub>hot</sub>	Efficiency
VISM (1993)	65.8	606	1407 C	31%
RASC (2003)	21.6	478	1200 C	23%
Venus Stirling (2007)	25**	58-138	850 C	17%

\*includes both mechanical and electrical power

\*\*includes cooler mass





# Stirling High Temperature Materials Status

## Nickel base superalloy

- Current Stirling hot-end material (MarM-247) for the ASC/ASRG project designed to operate for **17 years** at **1120 K (847 C)**
- For Venus missions of less than 1 year, MarM-247 needs to be evaluated for potential use at temperatures up to **1250 K (977 C)**.
- The use-temperature may be able to be raised to as high as **1350 K (1077 C)**



MarM-247 heater head

## Refractory

- For higher temperatures, a different class of material would be required
- GRC conducted initial development of advanced materials (refractory metal alloys and ceramics) specifically for high-temperature Stirling applications



Although not fully mature at the present time, these advanced materials have the capability of operating at temperatures as high as **1450 K (1177 C)**.

Refractory metal casting for heater head fabrication



Improvements have been completed to GRC's high-temperature environmental creep facility

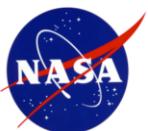
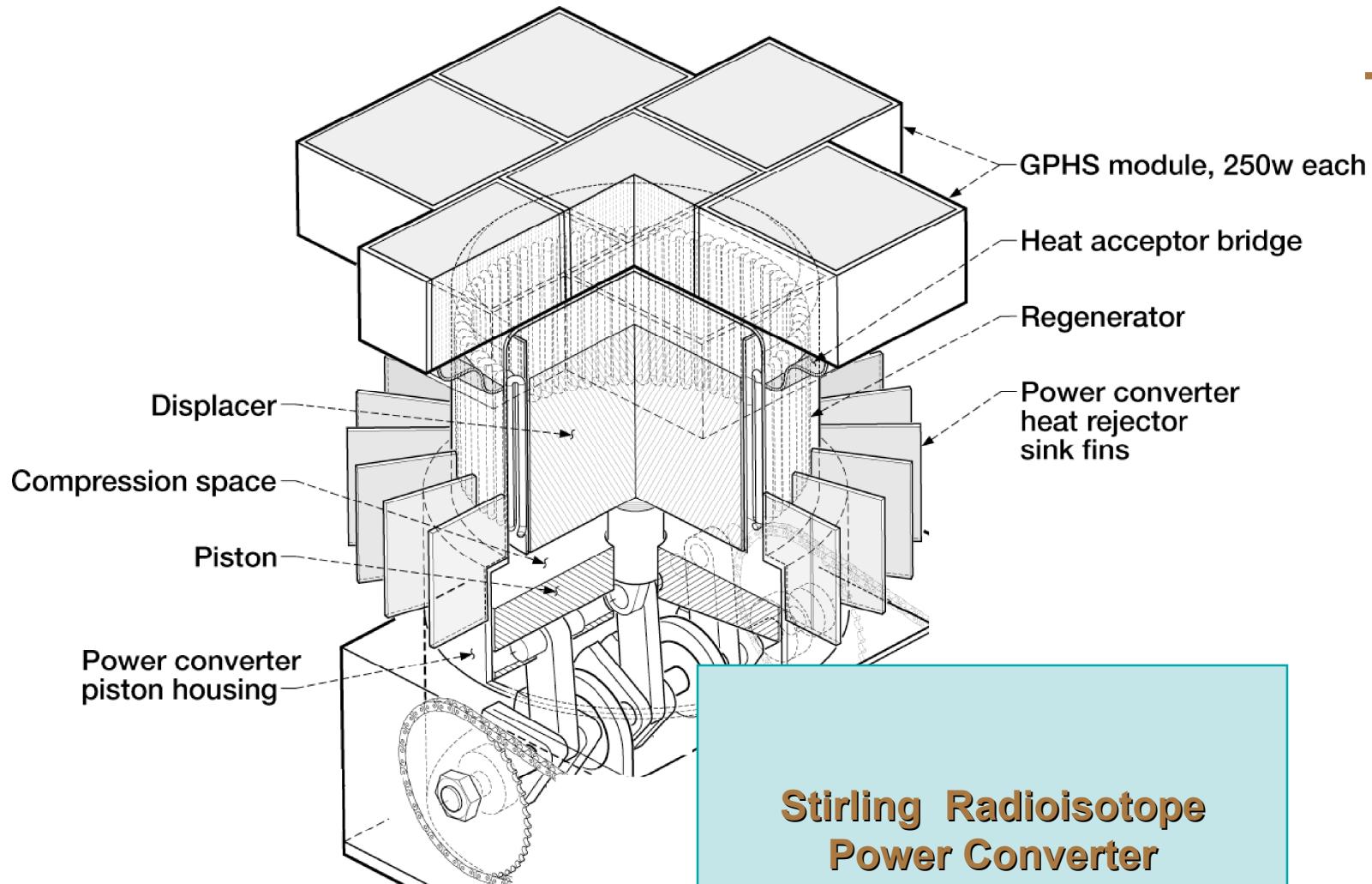


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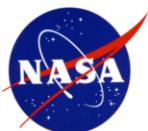
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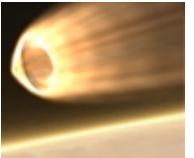


# Radioisotope Power: Sterling conversion

Parameter	Value
Type	Stirling cycle
Power output	478W
Source	7 250-W GPHS units
T (source)*	1200 C
T (sink)	500C
Heat input	1740 W
Heat rejected	1267 W
Overall efficiency	23.4%
Mass	21.6 kg



- Overall efficiency drops to ~17% for  $T_h=850$  °C



# Engines Operating at Venus Hot-end Temperatures

## ASC-1 and ASC-1HS

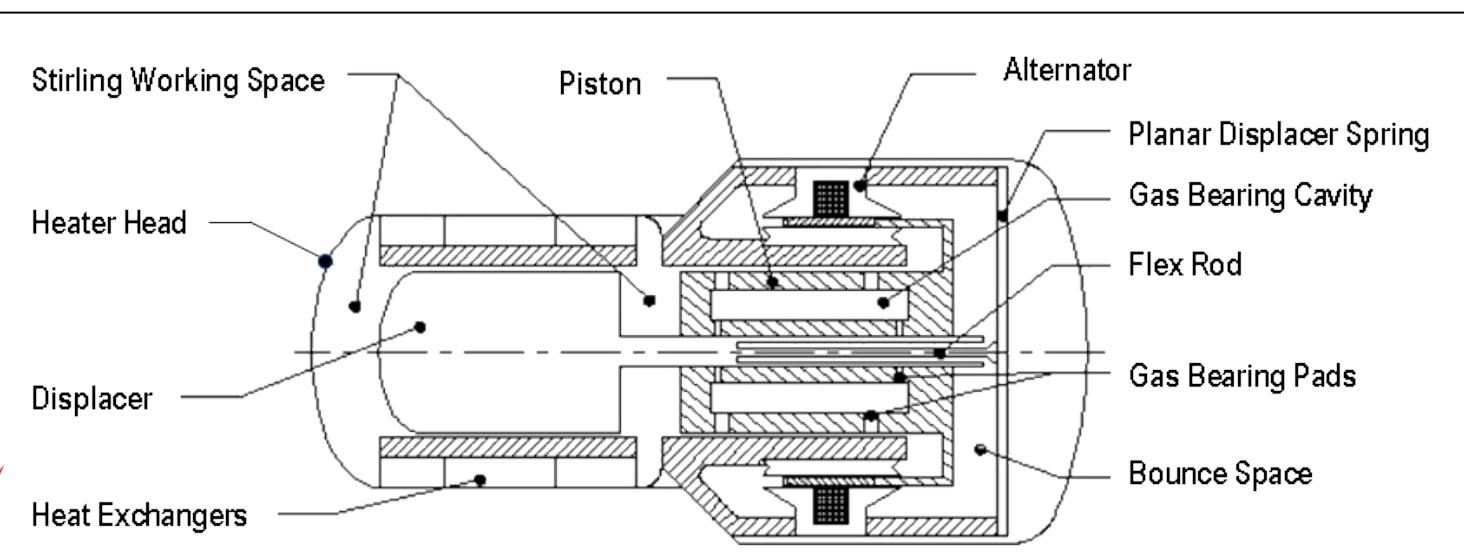
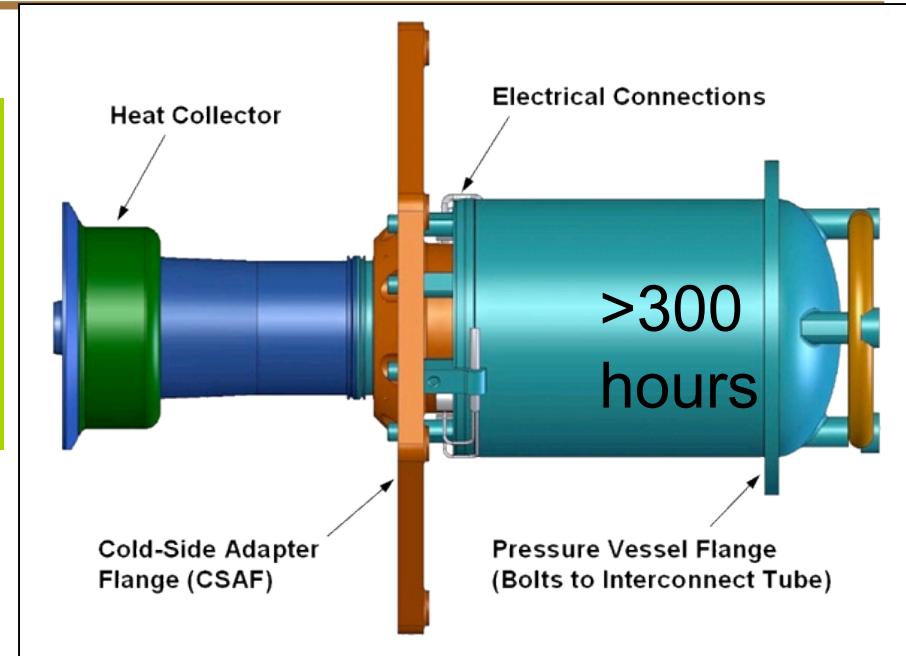
Single Convertor Operating over 300 hours

Total hours on all convertors: 1257

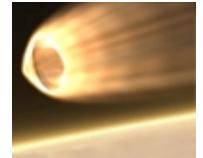
1123K hot-end

363K cold-end

38% efficient, 1.3 kg, 102 Hz,  
~3.6MPa, 88 W up to 114 W, 2005



# Engines Operate at Venus hot-end Temperatures



CTPC (Component Test Power Converter) Operated at:

**1050K hot-end,**

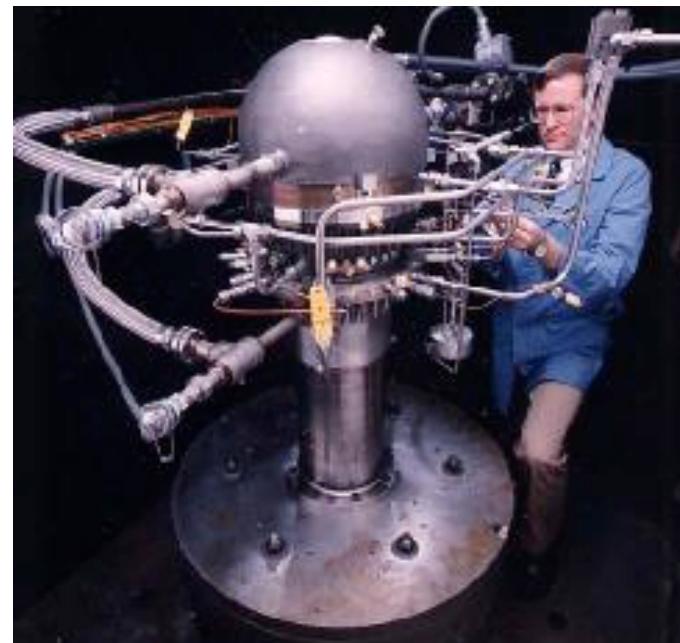
**525K cold-end,**

**3-4 hours at max. temp.**

**1500 hours total testing (800/400 K)**

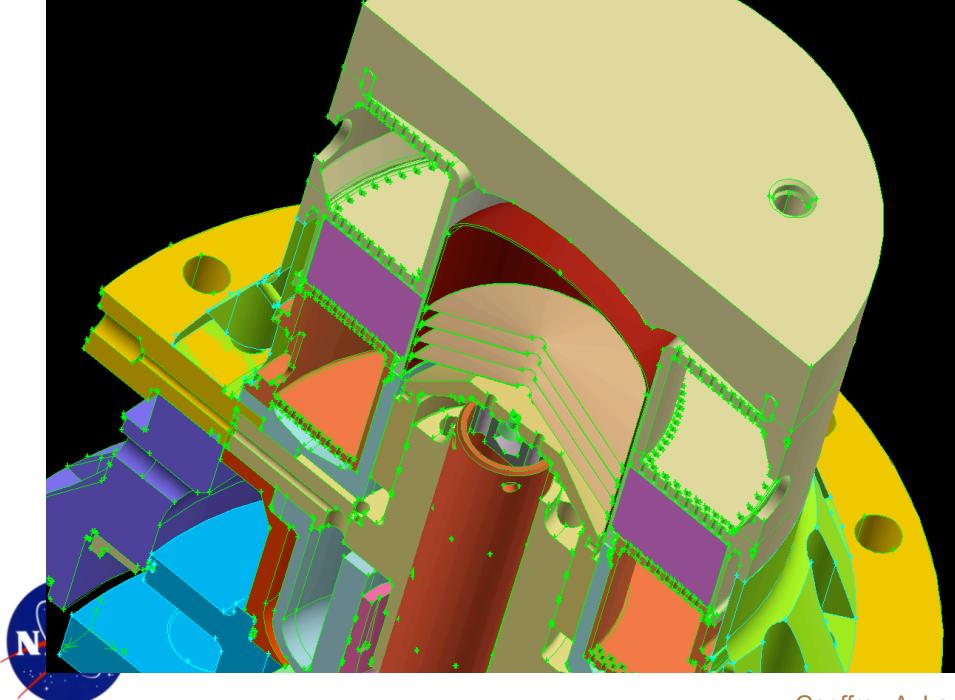
**70Hz, 15.0 MPa, 12 kW<sub>e</sub>, Nov. 1992**

CTPC Cold-end Testing

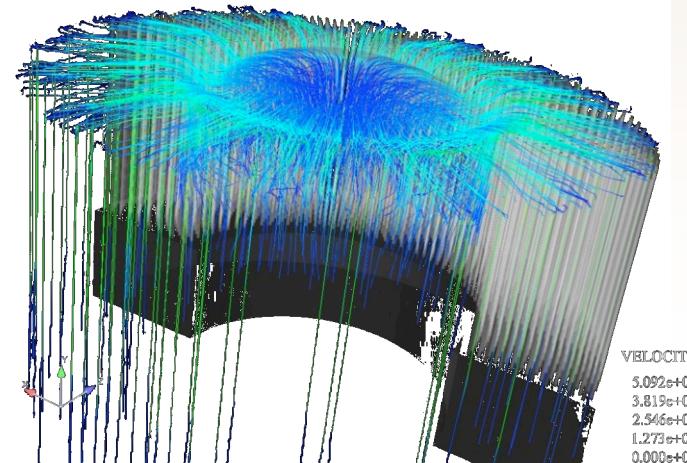


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Ref. T. Walter, P. Chapman



## Waste heat rejection

- High temperature of Venus atmosphere means that cold side of converter is >450C
  - This reduces the possible Carnot efficiency
- Venus atmosphere is superb heat sink
  - 150 times denser than sea-level air
  - High heat capacity
  - Good convection at Venus gravity
- Heat rejection fins are very small
  - 24 rectangular 5 cm x 6.5 cm fins
  - Cold side temperature can be very close to atmospheric temperature





## Interior Pressurant

- **Interior of electronics sphere is pressurized to Venus atmospheric pressure**
- Desirable properties of pressurant gas:
  - Transports to Venus in liquid form
  - Pressure of ~92 bar at operating temperature
  - Non corrosive
  - Low leak rate
  - Low thermal conductivity
- Pressurant picked: HFC 236fa

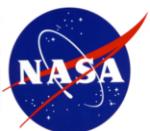




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## Properties of some candidate pressurants

gas	Liquid Density at 25°C (kg/m <sup>3</sup> )	Vapor pressure at 25°C (MPa)	Thermal conductivity [W/m <sup>-1</sup> K <sup>-1</sup> ]
helium	125	na	0.152
nitrogen	808	na	0.0258
argon	1400	na	0.0177
carbon dioxide	468	5.9	0.0167
Xenon	2953	6	0.00565
propane	500	0.9	0.0179
HFC-23	670	4.732	0.0131
HFC-236fa	1360	0.27	0.0042



# Properties of HFC 236fa pressurant

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6<sup>th</sup> International Planetary Probe Workshop, Atlanta, Georgia  
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- Stores as liquid for flight
- Vaporizes at operating temperature
- Inert
- Thermal conductivity 20 times lower than air
- Used as a fire suppressant: does not decompose to outgas of HF at high temperature

